SubsySTEM

1

SUBSYSTEMS1

Introduction to Electronics

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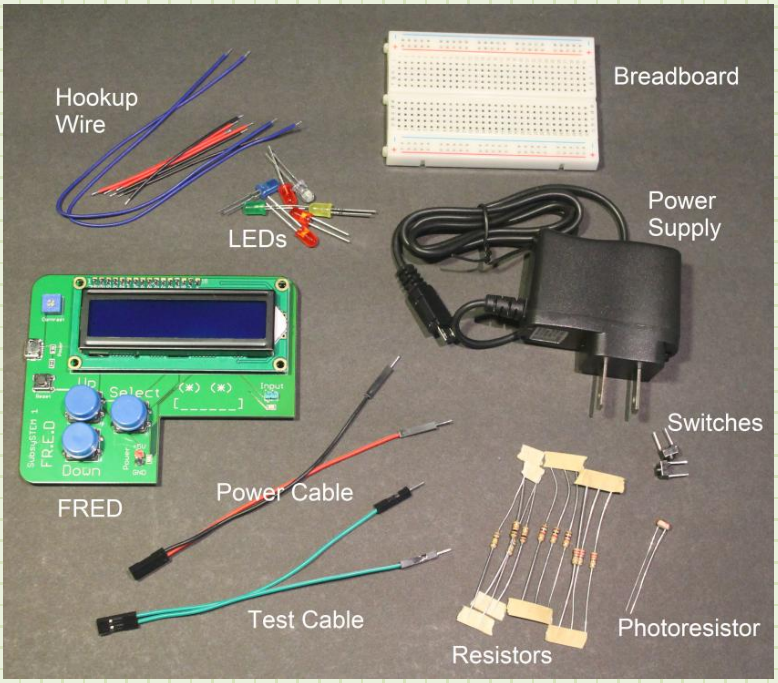
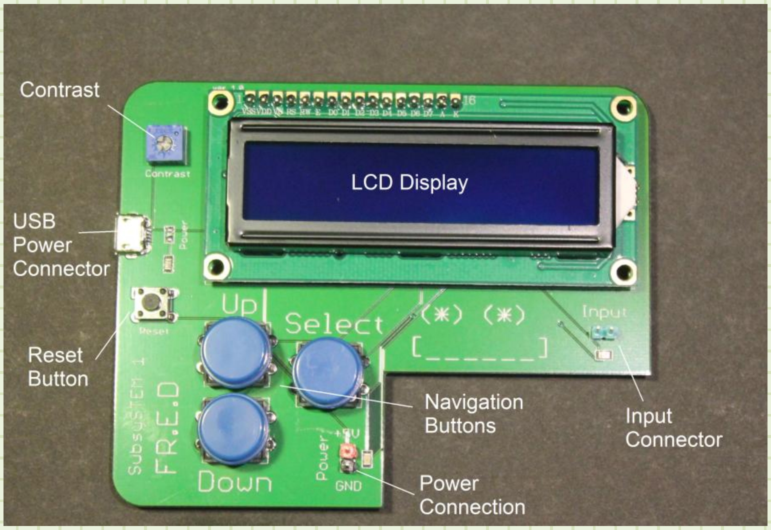
Hardware

Below is an inventory of your electronics kit.



And a close up of FREDs details:



Introduction

"The true sign of intelligence is not knowledge but imagination."
Albert Einstein

Welcome to this Subsystems Module. It is our sincere hope that it will be both an educational dive into electronics and an equally entertaining way to apply your new knowledge to practical experiments using FRED (our FRiendly Educational Device).

The format of these lessons will follow the same general pattern:

1. Concepts will be introduced
2. You will calculate expected values
3. You will experiment to confirm your results

Through this process, we hope you will be inspired to continue to learn about electronics and expand your interests into other Science, Technology, Engineering, and Mathematics (STEM) topics.

Objectives

This Subsystem unit is designed for someone with little to no electronics knowledge. It will introduce simple concepts about electricity, how it travels through conductors, how we can harness it to do real work, how we can predict its behavior with a simple mathematical relationship, and how people can quickly assemble and use simple electronic circuits. Below is a list of the primary objectives of this unit:

After completion of this unit, the student will:

1. be able to explain the basic structure of an atom and why certain elements are better than others at conducting electricity.
2. be able to explain the concepts of a closed and open circuit and how current moves through each.
3. be able to construct simple complete circuits on a temporary building platform (breadboard) using conductors, electronic components, and a power source.
4. be able to explain the characteristics of Series and Parallel circuits to include the unique properties of each.
5. be able to calculate key electronic values of voltage and current through all components of a Series, Parallel, or compound circuit.
6. be able to explain how batteries and power supplies are connected in electronic circuits.
7. understand the basic idea of a semi-conductor and use Light Emitting Diodes in lighting and indicating circuits.
8. understand the use of common electronic test equipment.

In the process, we want you to begin to feel comfortable around electronic circuits, understand the dangers of high voltages, and begin to use the correct jargon when talking about electronic components and values.

Tools

To accomplish these objectives, you have a few tools at your disposal.

First, you have this curriculum guide. It will walk you step by step through the entire curriculum that includes the text, the academic exercises, and the lab exercises.

The next best tool is FRED. This computer will guide you through some of the exercises and act as a power generator, voltmeter, and fun companion through your studies. Let’s get to know him now.

1. FRED is powered by the included power adapter. He uses a standard micro USB connector. Ensure you line up the connector the correct way. You shouldn't have to force the connection. ***Plug him in now***.

2. The RESET button (labeled Reset on FRED) always brings you back to the main menu. Press it now. It is a good idea to reset FRED whenever you first turn him on.

3. At the Main Menu prompt, press the SELECT button and let FRED guide you through his introduction. He will introduce you to his navigation buttons and highlight some of the important connection locations.

The last tool you have is a breadboard and some useful electronic components. You will use these to create temporary circuits during the labs that will reinforce the concepts you learned. We'll also have some fun circuits and experiments that may require simple household items.

Well, that is it in the way of introduction. Get ready to enter the fascinating world of the atom, electronic circuits, and fun with FRED.

Module

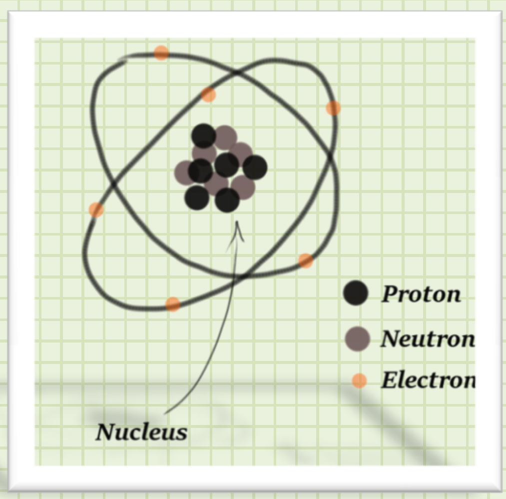
1

MOD1: Electricity

We begin our story on electronics with the ultra-small. The atom is the smallest particle you can have that still holds all of the properties of that particular material. For example, Carbon is all around us. It exists in the carbon dioxide we breathe out, the graphite that is in our pencils, and the diamonds we prize as valuable. It can look so different depending on how it is found in nature. But if we ask the question "What is Carbon?" we can reduce all of these complications to the simple answer: It is an atom.

The Atom

A person of about 150lbs is made up of almost $7x10^{27}$ atoms (that's a 7 followed by 27 zeros!!!!)



At left is a picture of a carbon atom. An atom almost looks like a small planet system with a main central body (the planet) and multiple orbiting objects (the moons). In this case, the planet is actually the **nucleus** of the atom. It is the center of the atom and is composed of tightly packed particles. These particles are ***protons*** and ***neutrons***. It is the number of protons in the nucleus that determine what element the atom is. For carbon, this number is 6. That means all atoms that have 6 protons in the nucleus are carbon atoms. This is also referred to as the ***atomic number*** of an atom. Amazingly, the same atom is used to construct graphite (often used in pencil lead) and diamonds. The difference is the way the carbon atoms are chained together. Protons have a positive electric charge. That means they will repel like charged particles and attract unlike charged particles.

Neutrons have no electric charge. They do not determine the type of element of the atom, but they do contribute to the weight. As stated above, the protons have a positive charge and the neutrons have a neutral, or no charge. So if like charges repel, why doesn't an atom just fly apart? The answer is that there is an amazingly strong attractive force exerted by both protons and neutrons called the ***strong nuclear force*** that glues the nucleus together.

Orbiting the nucleus is a cloud of ***electrons***. These are very small particles that move in distinct orbits around the nucleus. Electrons have a negative charge of the same strength as the proton's positive charge. Many atoms have the same number of protons and electrons which mean the two charges balance themselves out and the atom appears to be electrically neutral. When an atom takes on an extra electron, it takes on a net negative charge. If an electron is stripped off of a neutral atom, the atom will then have one extra proton than electron and will appear to have a positive charge. The ability for the electrons to move to and from atoms is the very basis of the study of chemistry. Through that mechanism, various atoms will transfer electrons or even share them with other atoms and create molecules and compounds. This is a huge field of study, but what we are interested in is the atom's ability to lose and gain electrons. This is going to be the heart of electric current flow and fundamental to our study of electronics.

Electrons

Because electrons are free from the gluing effects of the strong nuclear force, they can actually be coaxed into leaving the bonds of their atom and move to another atom or just ejecting clear of the atom itself. Electrons of different materials have different abilities to leave their respective atoms. Metals tend to have very loosely bound outer electrons and they zip about between the atoms as if they can't decide which to belong to. This free movement of electrons is the basis of electrical current in a circuit and we even refer to these electrons as ***free electrons***. If a material has a large amount of free electrons, it is said to have high conductivity and is referred to as a ***conductor***.

Other materials tend to hold on to their electrons and keep them pretty bound to the atom. In these materials, there are very few free electrons and the material does not conduct electricity well. We refer to these low conductivity materials as ***insulators***.

The chart below shows some typical materials and their relative conductivity.

Conducting Material	Conductivity
Silver	Increasing Conductivity
Copper	
Gold	
Zinc	
Nickel	
Iron	
Lead	
Sea Water	
Drinking Water	
Glass	
Hard Rubber	
Dry Wood	
Air	
Teflon	

Silver is an amazing conductor. It tends to be pricy for everyday use. Luckily, copper is cheap and an excellent conductor as well. That is why much of the wiring in electronic circuits is made of copper. The lower half of the chart shows materials that conduct so poorly we call them insulators. These materials still conduct, but very poorly. This makes them less likely to be used in electronics circuits as conductors.

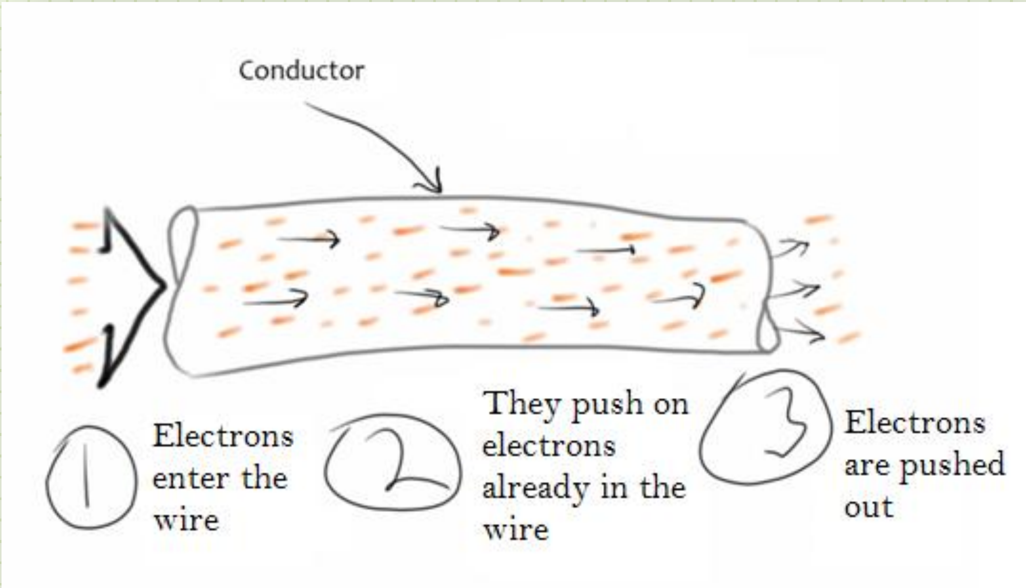
Keep in mind that the values of conduction are dependent on more than just the material. Temperature plays a huge role in conductivity. As temperature increases, the atoms of a substance start to vibrate more and more. For some materials, this tends to loosen up tightly bound electrons and the material conduction increases. However, some other materials that are normally good conductors can have the opposite effect. The crazy motion of the electrons can become so random that it is hard to get them to travel in the direction we want and the material becomes less conductive.

Since in electronics we are manipulating these free electrons to our benefit, we need these conductors to be able to carry the electrons around our circuit. We have already discussed the fact that atoms of our conductors have easily movable electrons available to us. Now we will discuss what that really looks like.

Let's say your friend asks you to water the garden vegetables. You head out to the garden, hook up the hose to the water supply, attach a trigger controlled nozzle to the other end and turn on the water. Initially, when you squeeze the trigger, there is a short delay until the water starts to spray out. From that point on, you can start and stop the spray without the delay you saw initially. You have probably easily figured out that it is because the hose started with no water in it and needed a short time to fill before water exited the nozzle. Once filled, water entering the hose at the supply connection pushes on the water already in the hose and immediately shows up as water pushed out of the nozzle.

This is the same concept that happens in our metal conductors. Since the atoms already have electrons present in them, more electrons entering the conductor will cause an immediate pushing of all those electrons and if there is a path for them to go, like the water spraying out the nozzle, they will follow that path. We can then use conductors to convey (or conduct) electrons around our circuit.

This is visually shown below:



As electrons are pumped into the conductor, they push on the electrons already there and cause the electrons to migrate down the conductor.

I mention the concept of electrons being "pumped" into a conductor. We now need to understand the concept of the "electron pump."

Voltage Sources

So conductors carry electrons around our circuit. But what is the source of this pumping force that actually gets them to move? To answer this, we need to understand some basic electronic terminology.

Voltage: Voltage is defined as an electromotive force or difference of potential expressed in **volts**. It is a measure of this “pumping force” that causes electrons to flow in a circuit. It is important to recognize that voltage is always expressed as a difference. This means it is measured relative to some other point. If I told you that I was five years older, you would probably ask "older than what?" Telling you I am older doesn't mean anything until I give a reference. If I say I am five years older than my wife, you may still not know how old I am, but you do know the difference in age between my wife and me. Voltage works like that. You have probably seen a 9-volt battery. It sounds like it is giving you an absolute voltage by saying it is just 9 volts. But what it really means is that it has 9 volts of potential between its negative and positive connections. Often, we will tie the negative side of the battery or power supply to a "common" return line in our circuits. We arbitrarily establish this as a zero-volt point in our circuits and we measure all voltages with respect to it.

Current: Current is a measure of the flow of electrons in a circuit. It is measured in **Amperes** or **Amps** for short. One ampere is a **Coulomb** number of electrons passing a point in one second. What is a Coulomb? Glad you asked.

1 Coulomb = 6.242×10^{18} = 6,242,000,000,000,000,000 electrons

That is a lot of electrons!! Because this number is so big, we often deal with current in milliamps (1/1000 of an Amp). For example, most computer USB ports limit the supply of current to 500 mA.

Resistance: Resistance is a measure of the opposition to current flow and is measured in **Ohms**. Resistance is anything that impedes the flow of electrons in our circuit. We will treat our conductors as though they have no resistance. But in reality, even the best conductors offer some resistance to current flow. A really thin wire may have around 1 Ohm of resistance for every meter. Most hookup wires (including the jumper cables we connect to FRED) have low enough resistance to assume a value of zero as we perform circuit calculations. However, if you run wires for long distances, you can no longer make this assumption.

Power: Power is the rate at which energy is transferred or consumed. It is measured in **Watts**, which is 1 **Joule** of energy per second. You might have noticed some strange names for these values. Volt, Ampere, Ohm, Joule, and

Watt were all men who investigated these concepts in electronics. Hey, when you discover something, you can name it after yourself too.

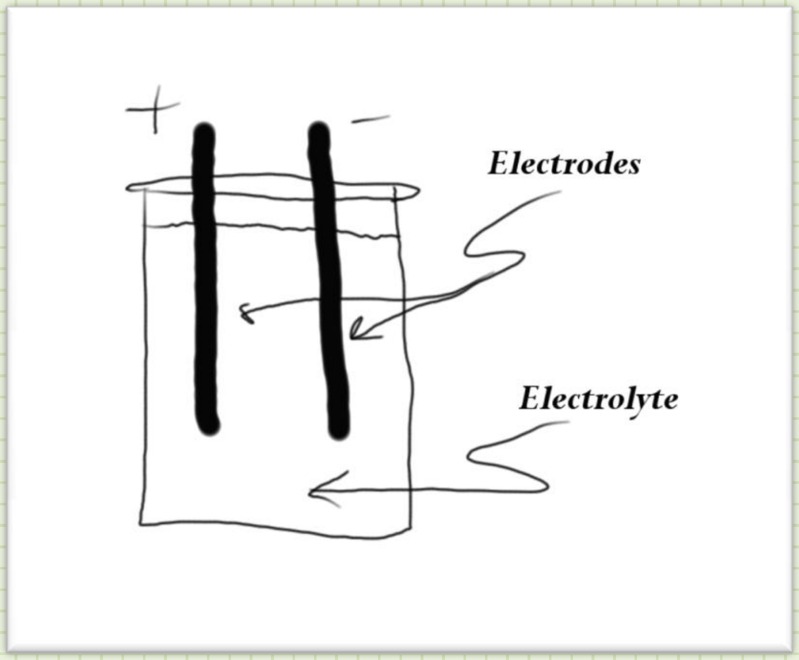
Below is a very important table. It lists these values, their symbols, their units, and the symbol of their units. Memorizing this table will give you the vocabulary to speak as an electronics technician.

Parameter	Abbreviation	Unit	Unit Abbreviation
Voltage	V or E	Volt	V
Current	I	Ampere (Amp)	A
Resistance	R	Ohm	Ω
Power	P	Watt	W

Notice a few things. Voltage can use the abbreviations of V or E. Since voltage is an electromotive force (abbreviated EMF), E has been used to stand for voltage in many applications. Also, you would think current would be abbreviated C, but the electronic value of Capacitance already took that so "I" is used. Some say that it stands for Intensity, since it describes how intense the electron flow is. But, if you search the web, you will see some varying views on this topic. Also, the unit of resistance is the Ohm, but the symbol for the unit is the Greek letter omega. "O" looks too much like a zero to be useful as a symbol so they went with the Greek omega. Now that we know what to call these, let's get on with our explanation of voltage sources.

Batteries

Batteries have been a common component of mobile electronics since there were mobile electronics. Most people are very familiar with AA and AAA batteries. These have been used for decades to power all of our toys, music players, remote controls, and so many other everyday items. Most people are also familiar with rechargeable batteries. They can be recharged over and over saving us a lot of money in replacement batteries and reducing the amount of toxic waste in our landfills. Batteries are small chemical factories that turn material into electron sources. Like a pump that raises pressure from its inlet to its outlet, batteries raise voltage from one end to the other. The chemistry involved in batteries is a little complicated but the basics are easy to understand.



We put two electrodes, one of a material that wants to give up electrons and one that wants to gain them in a conductive fluid (called an electrolyte). If we complete the circuit by allowing a path for current to flow from the negative to positive electrodes, the battery will supply electrons from the negative electrode and receive them in the positive while transferring ions between the electrodes through the electrolyte solution. This will continue until the chemical reactions are exhausted and the battery is dead. For some batteries, this means the end of its life. But we can formulate batteries to have reversible reactions. By sending electrons into the negative electrode and receiving the electrons from the positive electrode, we can create a chemical reaction that restores the battery to its original condition. This is how a rechargeable battery functions.

Solar Cells

Solar cells convert light into electric current. They work by using a material that has electrons in an outer orbit that can be excited (energy is transferred to it) to a state that allows it to break free. These electrons can then be conducted through an external circuit. Individual cells only put out a small amount of voltage and current, but, as we will learn more about in a later module, we can connect them in series and parallel to raise their voltage and current. You may have seen solar panels mounted on people's homes. Adding solar panels to your home is expensive, but it is a direct way that you can cut down on the amount of energy you take from the power grid and thus, save energy and reduce pollution. As scientist continue to increase the efficiency and lower production costs of these cells, you will see more and more people opting to add these devices to their homes.

Generators

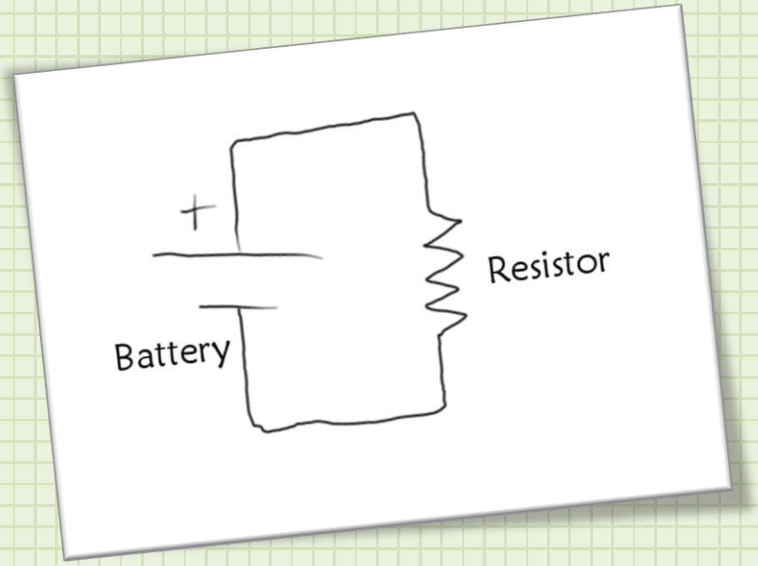
If you want to generate a lot of power, generators are the device of choice. There are many different types, but a simple generator consists of a rotating magnetic field and stationary coils. If we use some force to turn the rotating field, that field will generate a voltage in the stationary coils. We could use a water turbine, steam turbine, wind turbine, or other source for the mechanical turning force. Apart from the water turbines used in hydroelectric plants, most of our everyday power delivered via the nation's power grid system is made with steam driven turbines. We can burn coal, oil, natural gas, garbage, and even use nuclear reactions to generate the heat to make the steam. But in the end, that steam will turn a turbine attached to a generator.

Other Sources

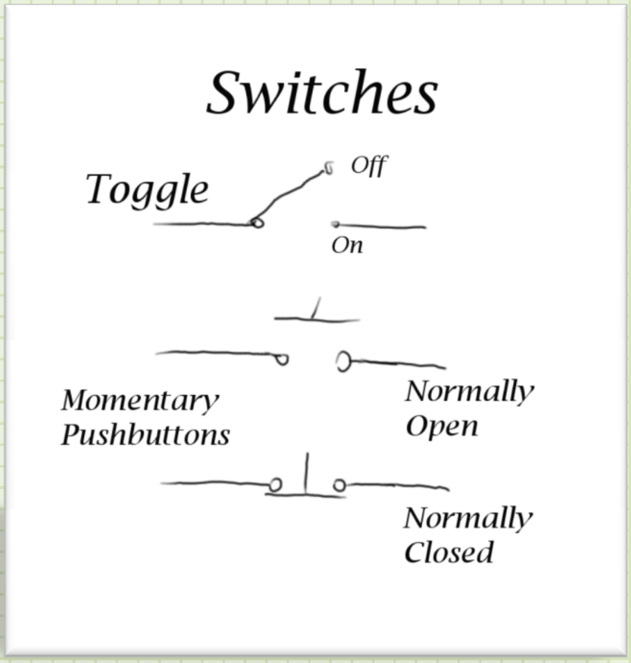
Power can also be generated in fuel cells which use hydrogen and oxygen to make electricity and water. There is a lot of hope that someday our cars may run off of this non-polluting energy generation. Geothermal power generation uses the difference in temperature at different levels in the Earth's crust to generate energy. Scientists are continually looking for new ways to produce power. Maybe you will be the one who develops a new clean source.

The Circuit

We have laid all of the necessary groundwork to start to discuss the concept of the electrical circuit.



Above shows a doodle of the most basic circuit there is. Here, a battery is connected via wires to a resistor. This also introduces you to the symbols that we use for wires, batteries, and resistors. Wires show up as solid lines that connect our components together. The battery symbol is two parallel lines. One line (the positive electrode of the battery) is slightly longer than the other. The resistor is a zigzag line symbolizing the difficulty current has from easily passing through this component. When we use the appropriate symbols for electronic components and show their interconnections with wires, we are creating what is known as a **schematic diagram** of the circuit. Below is the last schematic symbol I want to introduce you to right now.



Switches are fundamental to electronic circuits. They serve as an easy and safe way to start and stop current flow. Toggle switches are a type of switch that usually uses a lever or rocker to make electrical connection between its contacts or to break the electrical connection. The easiest example is a light switch. Put the switch in one position and current flows from the house supply, through the switch, and to the light to turn it on. Place the switch in the other position and current is interrupted and the light turns off. The other two switches in the picture are momentary pushbutton switches. These are operated by pressing them. A normally open pushbutton switch opens the circuit and prevents current flow until the button is pushed. A normally closed pushbutton allows current to flow through it until the button is pushed.

Since the power supply supplies our circuit with electrons and then creates a positive reception area for them, anytime we can create a conductive path from the negative to positive poles of a power supply, we can get electrons to flow through our circuit. When we achieve this, the circuit is said to be a **Closed Circuit**. When we put a significant enough resistance in the conducting path (like opening a switch or cutting a wire), we stop the flow of electrons from the battery and the circuit is said to be an **Open Circuit**. Some people get confused because when they hear open and close they think of a door. But when a door is open, people can pass through it and when it is closed, the flow of people stops. This is the opposite of how we refer to it in electronic circuits. It is better to think of a drawbridge. When a drawbridge is open, no cars can travel through. When the drawbridge is closed, the flow of cars can continue.

Let's put some of this new knowledge into practice. Get out FRED, your breadboard, and the electronic components and let's look at making complete circuits.

MOD 1: LAB

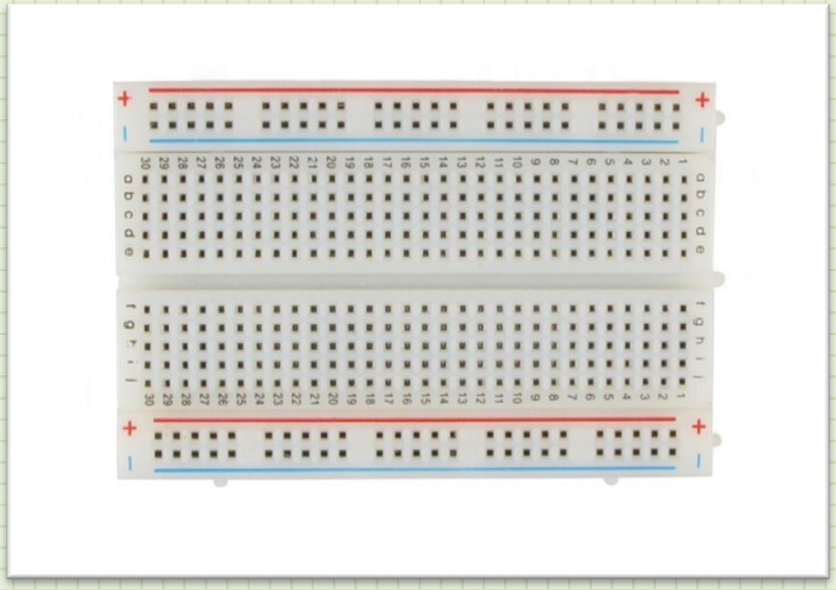
Objective: Get familiar with the breadboard, some basic electronic components, and build circuits that demonstrate open and closed circuits.

Materials: FRED, breadboard, electronic components, hook up wires, various household materials (discussed later).

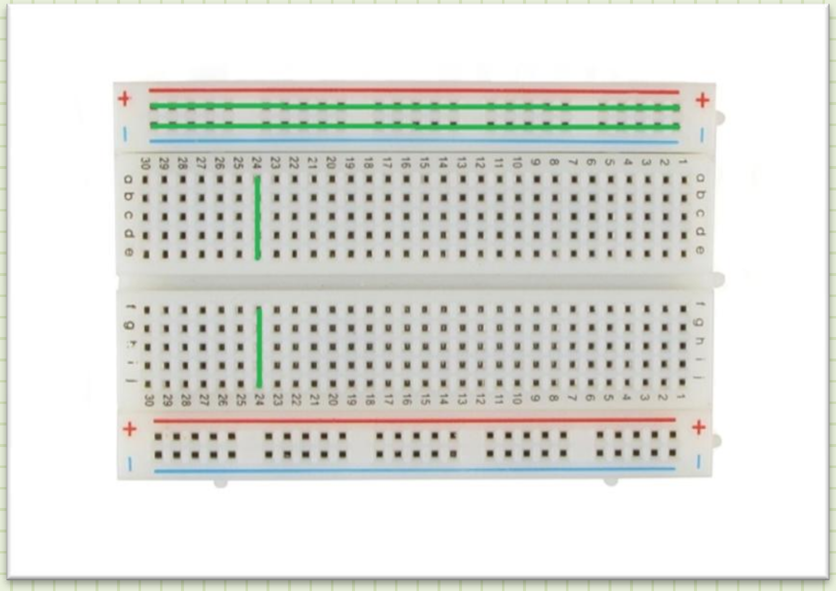
Procedure:

First, since this is the first time we are using a breadboard, let's look at what it is and how to use it.

A breadboard is an electronic prototyping device that allows you to quickly assemble circuits. After you are done, you can remove all of the components and reuse the breadboard for another circuit. It gets its name from the early days of electronics where people would hammer nails into a literal wood bread board and wrap components and wires around the nails to create circuits. Below is a picture of the breadboard included with this module.



The bread board is laid out with 2 rows of holes on the top and bottom. Each row of holes is electrically connected together. That means, whatever we plug into those holes will be connected to anything else in the other holes in the row. The upper row has a red line that runs down it and it is labeled with a red + symbol. The line of holes right below it is blue and marked with a - symbol. This will be a convenient place for us to hook our power to so that we can easily access it anywhere on the board. We will normally hook up the breadboard in the orientation you see in the picture. The Red (+) supply line on the top and the Blue (-) supply line on the bottom. The rows labeled with numbers in the middle of the board are also electrically connected together. That connection is broken in the very center of the board by that small valley in between the letters e and f to allow mounting of electronic integrated circuits. The green lines on the diagram below show you a sample of the places that are connected together internally in the board.



The holes themselves have small metal receptacles that grab on to leads of components and wires that we stick in them. By placing the components in specific places and using the conductive paths of the breadboard, we can create complete circuits quickly. As a note, new boards tend to be a little finicky. Sometimes it is hard to get wires to go in and sometimes when they are in, they can make poor contact. With use, most boards loosen up and become more conductive. If you are having problems with certain labs, check the connections and consider moving connection to different rows on the board. We are starting by looking at closed and open circuits, so we can begin by using FRED to check the integrity of our breadboard contacts.

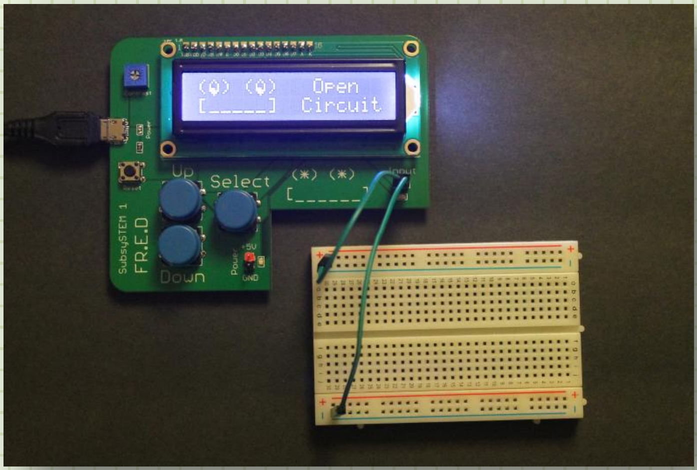
Perform the following:

1. Power up FRED as you did in the introduction.

2. After FRED finishes booting up and you see the Main Menu screen, press the **down** navigation button until you see MOD 1. If you pass it, just press the **up** navigation button to get back to it. This will open the Module 1 lab area. When you press the **Select** navigation button, FRED will show you where to hook up the test connector. You will then see FRED and the words “Open Circuit.” FRED is now ready to detect when he sees an open and closed circuit.

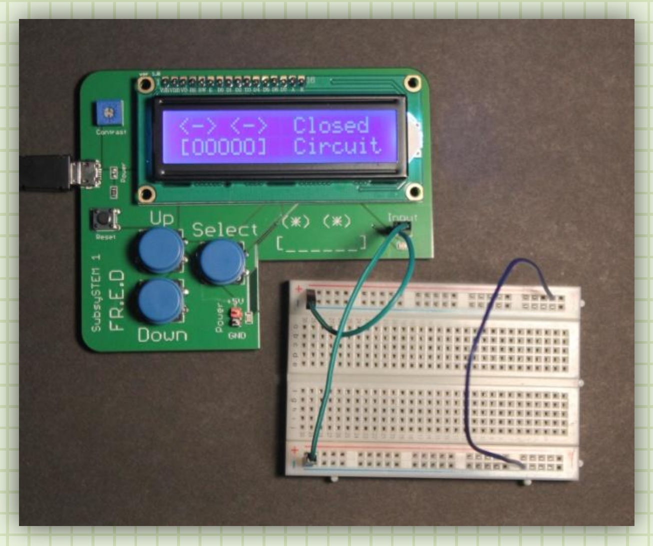
3. Connect the test cable to the connection that FRED showed you. It is marked Input on the board.

4. Connect one of the test cable ends to the upper Red power line. Connect the other to the lower Blue power line.

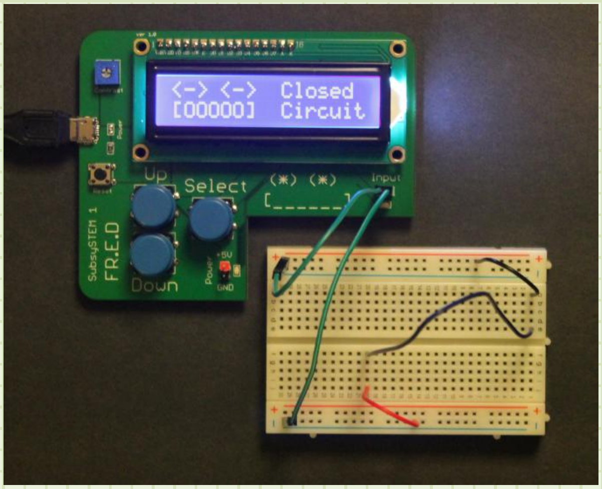


5. You now have the lab setup. FRED is constantly looking at the two connections to the board. Whenever he sees that a complete path for current flow has been established, he will indicate this by changing his expression and displaying the text "Closed Circuit."

6. Let's verify everything is working. Take a blue hookup wire and connect the top Red power line with the bottom Blue negative line. This connects the two lines from FRED together and completes a path between them. This should cause FRED to respond with the "Closed Circuit" display. If he does not, check your connections. While FRED shows "Closed Circuit," wiggle the wires around to see if you can get the circuit to show "Open Circuit" on FRED. This might be caused by a poor connection that is closing and opening as you wiggle it.

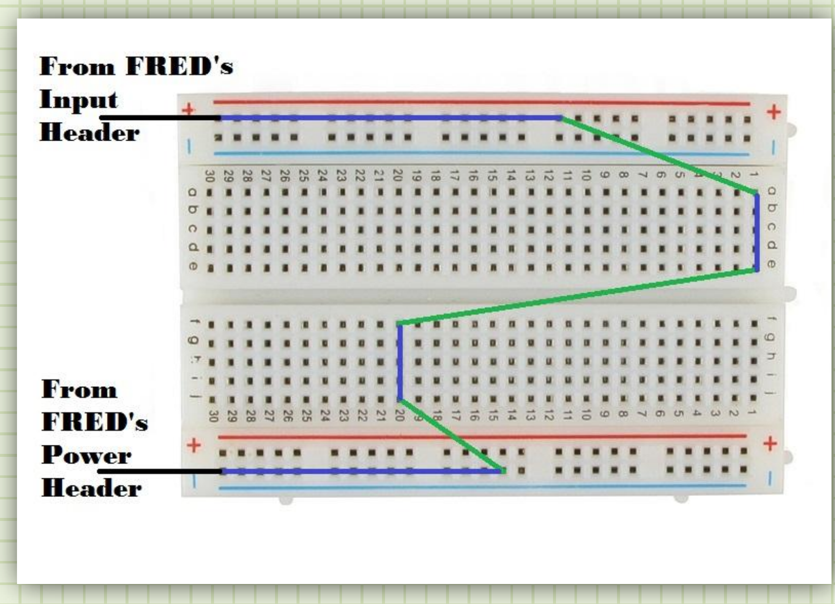


7. Remove the jumper from step 6. Let's make a little more complicated circuit. Insert one end of a jumper wire into the Red breadboard power header and the other into spot 1a (row 1, column a). Now take another jumper and insert it in 1e and connect the other end into 20f. Now take one more jumper and insert one end into 20j and the other into the breadboard lower Blue power header. What does FRED say? Can you explain?

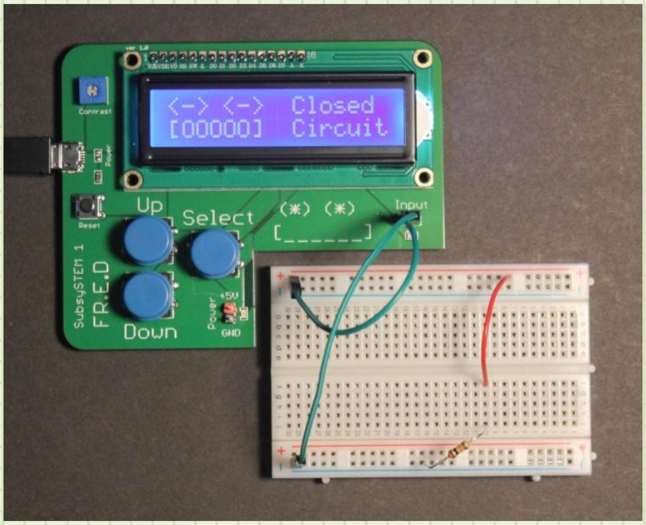


Your setup should look similar to the above.

Let’s look at what is happening on the board. Remember that anytime you complete a circuit from the top Red header to the lower Blue header, you have a complete circuit from FRED and back to him. The blue lines represent the conductors in the breadboard and the green lines represent the jumper wires. The combination of these two conducting systems (the breadboard and our jumpers) has completed a circuit.

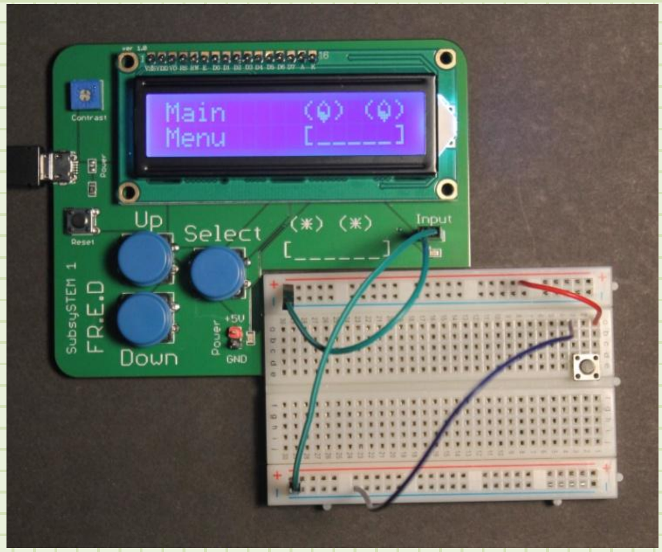


8. Let's try another one. Place one end of a jumper wire in the upper Red power header on the breadboard and the other end to into point 10f. Now take one of the resistors in the kit (we will talk much more about these components in the next Module) and bend the leads and insert one side into 10i and the other into the lower Blue power header on the breadboard. What does FRED think of that? FRED thinks there is a complete circuit.



We talked about resistance already. It is a material's ability to resist (or oppose) current flow. Even though resistors impede the current flow they do not stop it completely. Because they allow current to flow through them, they are still conductors. And when we use them in circuits, we have to remember that current still flows through them.

9. Remove the resistor. Move the jumper wire end from point 10f to 1a. Now take a pushbutton from the kit and insert it so that the pins are inserted into points 1e and 3e. Sometimes you may need to work with the component to get it into the breadboard and make good connections. Try not to force it too much. Connect another jumper from point 3a to the lower Blue power connector on the breadboard. Note that FRED is still registering an open circuit. Now press the switch.

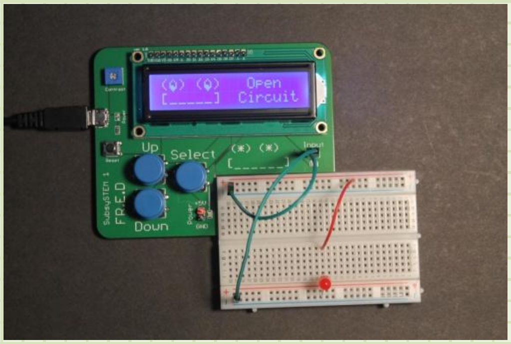


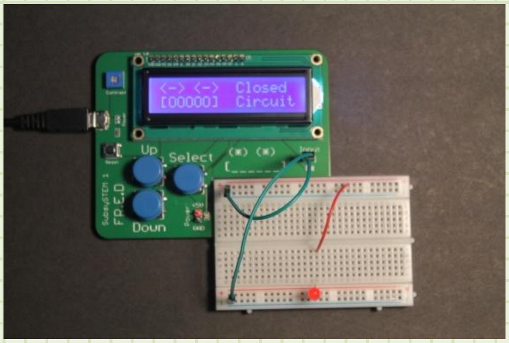
Remember that the switch opens and closes circuits. FRED responds confirming this. When you release the switch, the circuit is open again.

10. Remove the switch and jumpers from step 9. Now let's look at some household items and test their ability to conduct electricity. Grab some coins, aluminum foil, paper, and a pencil. Remove the test cable wires from the breadboard but leave them plugged into FRED. Now take the two wires of the test cable and, without touching the wires together, place them on the objects you collected and see what FRED says about their conduction. It should be no surprise that the coins and the foil conduct electricity. We already discussed that metals tend to have excellent conductivity. Now test the paper. It doesn't look like it conducts. Now take a pencil and draw an inch-long line on the paper moving the pencil back and forth along the line to make it really dark and thick. Now touch your probes to either side of this line. Does it conduct? If not, make sure the line is really dark and you can move the probes closer together (but do not touch them together). You should see that the pencil lead conducts. That is because it is not actually lead but graphite, which is conductive. In fact, some resistors are made of this same graphite. Try other materials. Lastly, try a little cup of water. Place the ends of the probes in the water (again, don't let them touch). Is the water conducting enough for FRED to register it? When I did it, it was. If isn't for you, try adding a pinch of salt. We tend to think of water as a good insulator and it is. But water is very rarely pure and any other materials (salts, minerals, metals from the city piping

systems, etc.) can make it conductive. That is why it is important to get out of the ocean and pools when there is storm activity in the area. The salts in sea water and the chemicals we add to pool water make it very conductive compared to pure water.

10. Let’s try one more item. Remove any resistors or wires still on the breadboard. Plug the test cable ends back into the upper Red and lower Blue power headers on the breadboard as they were before. Insert a jumper wire into the top Red power header on the breadboard and the other end into point 15f. Now take one of the Light Emitting Diodes (LEDs) from the kit (any color). Notice that one of the leads coming from the LED is longer than the other. Bend the leads so you can connect the LED in between the lower Blue power header and hole 15i with the long leg of the LED being plugged into the Blue header. What do you see? Is the light on? What does FRED say? If you hooked this up right, the light will be off and FRED will report open circuit. I guess this component must be an insulator right? Just for fun, spin the LED around and connect it so the short lead is in the Blue header and the longer lead is in 15i. What happened? The LED is on and FRED reports a closed circuit. What is happening? Well, LEDs belong to a group of electronic components called **semi-conductors**.





Semi-conductors have properties of conductors and insulators. Diodes work by only let current go one way through them. When you turn them around, they stop conducting. We will talk a little bit more on this class of component in a later MOD.

Conclusion

In this Module, we learned about the atom, conductors, insulators, and important electronic terms. We learned that Voltage is the "pressure" or driving force that allows electrons to flow in a circuit. We learned switches open and close circuits allowing and preventing current to flow. We briefly covered power sources and the basics of battery operation. Finally, we went to the lab to create complete circuits and look at different materials and their ability to conduct.

The next module will introduce you to the Series Circuit and will show you how you can predict electrical values using Ohm's Law.

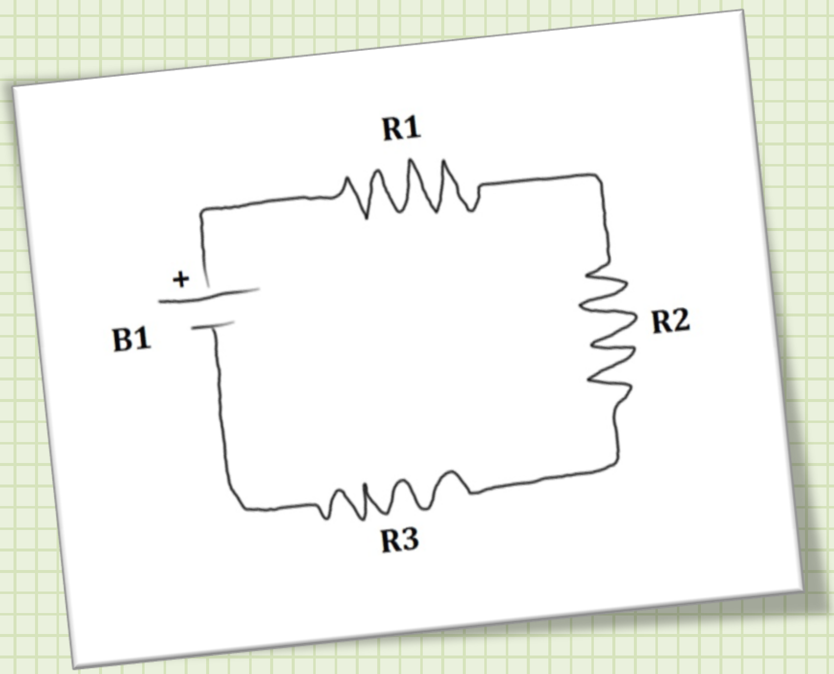
Module

2

MOD2: Series Circuits

Now that we have the fundamentals of electronic current flow, we need to start to understand exactly how it flows and how we can predict its behavior in our circuits. We will start with a circuit where the current leaves a source, travels sequentially through all the components, and then returns to the battery. This type of circuit is called a **series circuit**.

The Series Circuit



The above schematic is that of a simple series circuit. The battery (labeled B1) is the source of current flow in the circuit. It pumps in electrons which are carried by conductors through each resistor and then back to the battery. As we learned in the lab, resistors resist current flow but do not stop it. Therefore, since there is a complete circuit for current to flow out of the battery and return, there is current flow in this circuit.

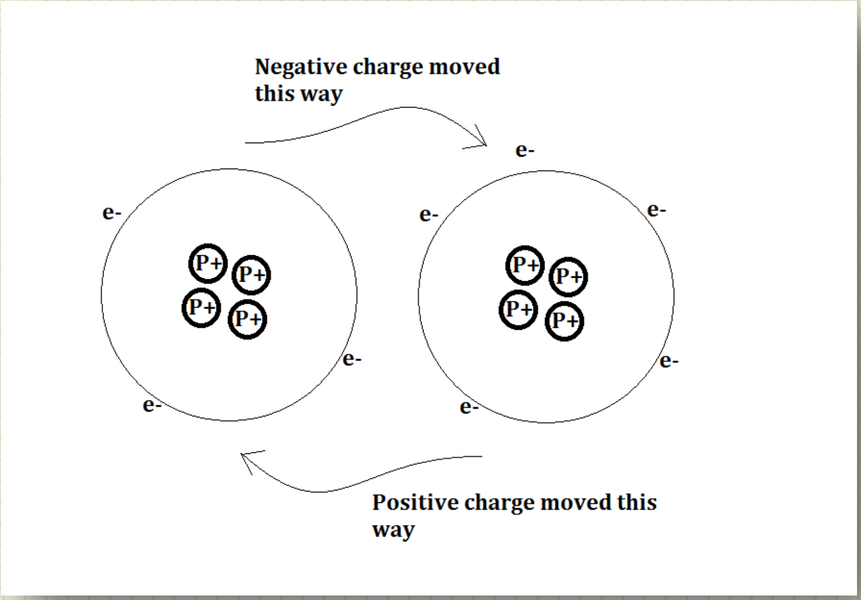
This is a good time to talk about current flow.

Current Flow: Positive or Negative - You Decide

We have discussed that electrical current flow leaves a battery, runs through a circuit, and returns to the battery. And we have also stated that a battery has a positive and negative terminal. It is quite easy to conclude that the current leaves the positive terminal, runs through the circuit, and enters the negative. You would make that assumption based on your observation that things in nature tend to go from high to low. After all, water doesn't flow up hill, it flows down. Pressure doesn't go from low to high naturally. If I open my kitchen faucet, water flows out because it is at a higher pressure than the atmosphere. We have the sense that things flow from high (or positive) values to low (or negative) values.

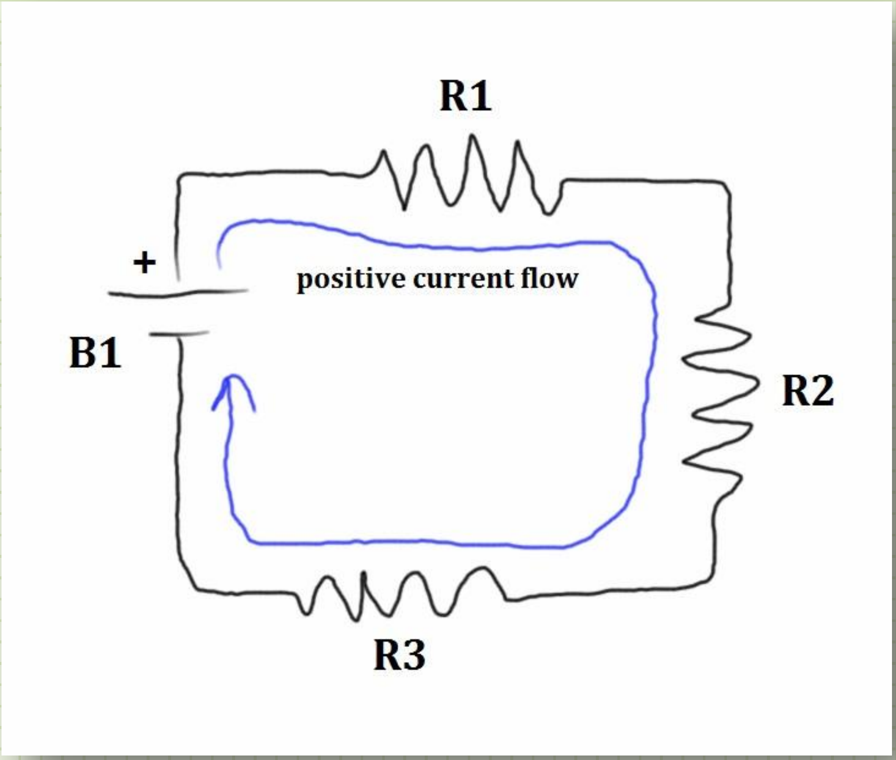
But, suddenly you realize that we also discussed that current is the movement of electrons through a circuit and that electrons are negatively charged. So surely, current originates in the negative terminal of a battery and is received in the positive. So current must go from negative to positive. Right?

Believe it or not, we owe Benjamin Franklin for this confusion. When he was studying the movement of electric charge during static electricity experiments, he saw that charge moved from one material to another. He correctly assumed that a single charged particle was moving from one to the other making one more positive and the other negative. When he established the direction of current flow, he guessed wrong at which material was actually gaining the particles and set the precedence for electrons to be considered to have a negative charge. By the time the true nature of electrons and current flow were fully understood, this convention of charge flow established by Franklin was so ingrained that it remains to this day. Usually, when electronics is first taught, the students are taught **electron flow** since this is the easiest to understand since we define current as the movement of electrons through a circuit. Because the naming of this direction of charge flow was arbitrary, many people decide to view current as the movement of positive charges through a circuit. Where do the positive charges come from? If you remember our discussion of the atom, protons have a positive charge. As an electron is stripped from an atom, it leaves a positive charge behind since the atom now has one more proton than it has electrons.



If we start with two atoms next to each other, each having 4 protons and 4 electrons, they both start off with a net zero charge. Now put a voltage across this material and watch as the electron jumps from the first atom to the next. The atom on the right now has 5 electrons and 4 protons with a net negative charge due to the extra electron. But the left atom has changed too. It has 4 protons and 3 electrons for a net positive charge. So whether we look at the movement of the electrons to the right or the movement of the positive charges to the left, it really doesn't matter. Most science and engineering classes have adopted this positive current flow (sometimes called "hole flow" because of the "hole" the electron leaves behind when it moves). It is referred to as **conventional flow** and is what we will normally use when tracing out current flow in a circuit in these modules.

That out of the way, we can get back to our discussion of the series circuit.



No we can look at the actual flow of current in this circuit. Current leaves the positive terminal of the battery (conventional flow), enters into the first resistor R1. It leaves that resistor and continues to flow into the second resistor R2. It leaves R2 and flows into R3 and then returns to the battery's negative terminal. Notice that the exact same current went through each part of the circuit. Current wasn't added or removed at any point. This is what defines a series circuit.

Current is the same through the components of a series circuit.

It is easy to get confused because of what we know of a resistor. If a resistor impedes (slows down) current flow, then if 1 Ampere of current enters it, shouldn't less than 1 Ampere get out of it? When we talk about current being impeded, we are referring to the amount of electrons able to get through the resistor and not the speed of travel of the electrons. Think of a crowd waiting to get into a concert. They wait at the front door until it is open. When it is, they rush to enter the concert hall. Because the entrance is small, it backs up people and the amount of people able to get into a single door is far less than if there were multiple entrances. This is the same idea behind a resistor and current flow. The battery will supply circuit current that is proportional to the resistance in the circuit. This is exactly what Georg Simon Ohm discovered. He experimented with a power cell and various materials to discover that the flow of electricity is related to the voltage across the object and the objects ability to resist the current. The resulting electronic law is called **Ohm's Law**.

Ohm's Law

Ohm was a German schoolteacher and experimenter. He made the observation that if you connected a voltage source across a material, you would see a current running through the circuit. If you increase the voltage and keep the material the same, he noticed that the current increased. And if you kept the voltage constant and changed the material, the current would change. He would express this rule as a mathematical equation that would be referred to as Ohm's Law.

$$\boldsymbol{Resistance\ (R) = \frac{Voltage\ (E)}{Current\ (I)}}$$

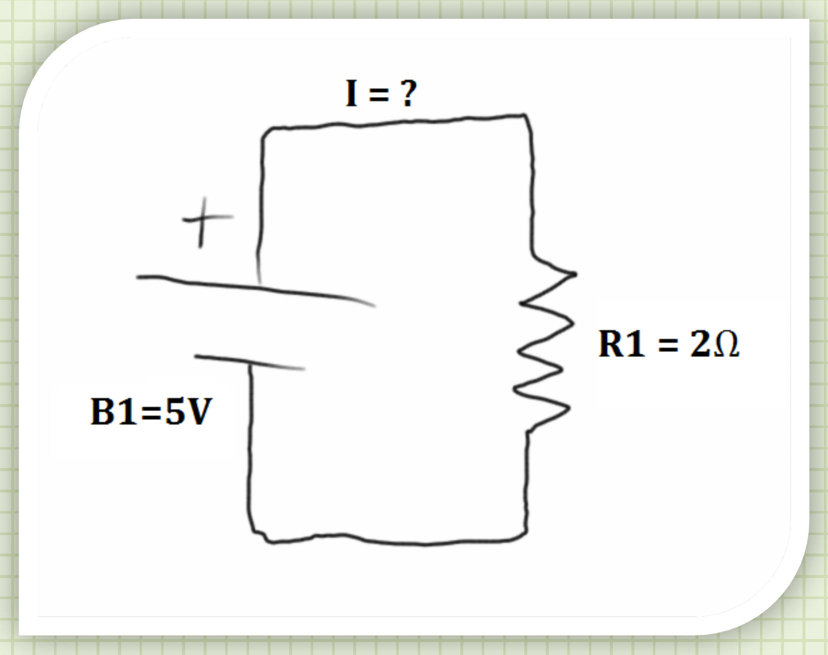
Using our symbols and rearranging the terms we get the following relationships:

$$\boldsymbol{R = \frac{E}{I}}$$

$$\boldsymbol{I = \frac{E}{R}}$$

$$\boldsymbol{E = IR}$$

These relationships are going to allow us to predict the behavior of circuits. For instance, let's look at the circuit below:



In the above simple circuit, the battery is supplying current at 5 volts, and the circuit is offering a resistance of 2 ohms. Using Ohm's Law, we can actually calculate the resultant current.

For the Circuit: $I = \frac{E}{R} = \frac{5\ V}{2\ \Omega} = \mathbf{2.5\ A}$

Notice that I started the line with "**For the Circuit**." This was a very intentional step to ensure that I wasn't applying Ohm's Law around something that it doesn't apply to. Initially when people learn Ohm's Law and go to apply it, they have a tendency to grab ANY voltage, ANY resistance, or ANY current and plug them in assuming the answer is what they were looking for. Ohm's law is meant to be applied over a specific part of a circuit (like a component or group of components) or the circuit as a whole. By starting our calculations with the target component written clearly upfront, we can help prevent using the wrong values in our calculations. For our example, we had only one voltage and one resistance so this was not an issue. As we move on and circuits become more complicated, this will not be the case.

Ohm's Law is set up to work with the base unit of resistance, voltage, and current. That means, if you put in Volts and Ohms, you get Amps out. If you put in Amps and Ohms, you get Volts out, and so on. Using the base units will remove some confusion when using unit modifiers like kilo and milli.

But in electronics we are often working with very large or very small numbers. So we turn to the metric system for help. You probably have some experience with the metric system and its use of multipliers to make expressing numbers easier. You may be familiar with expressing measurements like one thousand meters as a kilometer and one thousandth of a meter as a millimeter. You probably are also familiar with these multipliers when talking about computers. Your computer speed may be 3.2 Gigahertz and its memory may be 8 Gigabytes. We use these same multipliers in electronics to make expressing the very large and very small easier. We may refer to a milli-amp (one thousandth of an Amp), or a kilo-ohm (one thousand ohms). In electronics, we tend to stick to the multiples of 1000. Below is a table of the multipliers and their symbols.

Name	Symbol	Multiplier	
Giga	G	10^9	1,000,000,000
Mega	M	10^6	1,000,000
kilo	k	10^3	1,000
milli	m	10^{-3}	0.001
micro	µ	10^{-6}	0.000,001
nano	n	10^{-9}	0.000,000,001
pico	p	10^{-12}	0.000,000,000,001

You may already know how to convert between multipliers, but let's review one method that works.

Multiplier and Unit Conversion

First, let's review a couple of quick algebra rules:

1. Anything divided by itself is equals 1.
2. 1 times a number just gives you that same number back.

When we want to express a large or small number in another unit, we don't want to change the VALUE of the number but just the WAY the number is reported.

For instance, if someone asked you how tall you were and you said 5 ft, he may want you to report it in meters. He wants to know the same VALUE (your height) but he wants it expressed in his desired units. So let's use the above 2 algebra rules to do this:

First, find a relationship between feet and meters:

$$1\, meter = 3.28\, feet$$

Now, divide both sides by the unit you want to convert from (in this case, feet).

$$\frac{1\, meter}{3.28\, feet} = \frac{3.28\, feet}{3.28\, feet}$$

Using algebra rule 1, the right fraction becomes 1.

$$\frac{1\, meter}{3.28\, feet} = 1$$

Now, take our original value that we wanted to convert (5 feet) and multiply it by our fraction. Remember, our fraction equals 1 and by algebra rule 2, we can multiply by it and not change the original value.

$$5\, feet\ x\ \frac{1\, meter}{3.28\, feet}$$

Since we have feet on the top and feet on the bottom, by rule 1, this equals 1 so we can cancel them out. You are left with a final equation. Use a calculator to solve.

$$\frac{5\ meters}{3.28} = \mathbf{1.52\ meters}$$

Now you can tell your friend your height in his preferred units.

Let's see how this works with multipliers. Let's say we measured the current in a circuit and it equaled 0.00245 A. This is an awkward number to talk about so we want to convert it into milliamps so it will be easier to express. We need an expression to relate amps to milliamps.

$$1\ A = 1000\ mA$$

then divide by what we are converting from (A). Apply rule 1.

$$\frac{1\ A}{1\ A} = \frac{1000\ mA}{1\ A}$$

$$1 = \frac{1000\ mA}{1\ A}$$

Now multiply the original by our conversion fraction and apply the algebra rules.

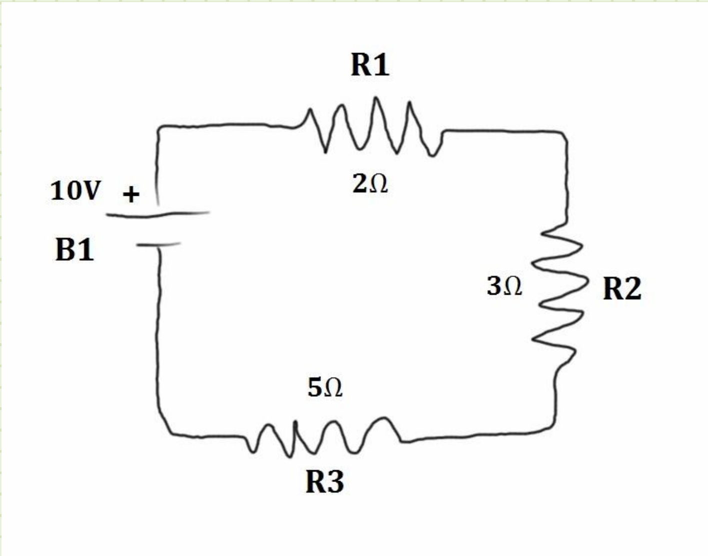
$$0.00245\ A\ \ x\ \frac{1000\ mA}{1\ A} = \ 2.45\ mA$$

So this means that 0.00245 Amps is equivalent to 2.45 mA. It is a lot easier to refer to this current as 2.45 mA then the large number with lots of zeros.

Whether you use this method or some other method, make sure you feel comfortable converting between units and multipliers. We will use base units (V, Ω, A) in our calculations, but will report the answers in convenient units.

Let's do a more complicated example. Let's create a circuit supplied by a 10 Volt battery. We will then hook up 3 resistors in series with the values of 2Ω, 3Ω, and 5Ω and connect it to the battery. We need to find the current in the circuit, and then all of the voltages across the resistors. We have discussed the concept of voltage supplies, but in our circuit, we are about to find out that resistors are voltage consuming devices. Ohm's Law states that Voltage is equal to Current multiplied by Resistance. That means when we have a resistor with current going through it, there will be a voltage developed across it. Let's do these calculations and find out what new Law is waiting for us at the end.

The schematic of our circuit is shown below:



The first thing we want to calculate is the total circuit current. Writing the Ohm's Law equation, we get

For the circuit: $I = \frac{E}{R}$

If our equation is for the circuit as a whole, we know we have the total circuit voltage, but do we have the total circuit resistance? We don't. We have three individual resistors. We need to figure out how to get the total resistance.

Combining Resistors in Series

Here is the great thing with series circuits. We can just add the individual resistors together to get the total circuit resistance. The formula is simply

$$R_{Total} = R_1 + R_2 + R_3 + \cdots$$

So, with this relationship, we can calculate the total resistance of the circuit and have everything we need to solve our equation for current.

$$R_{circuit} = 2\Omega + 3\Omega + 5\Omega = 10\Omega$$

For the circuit: $$I = \frac{E}{R} = \frac{10V}{10\Omega} = 1A$$

So the total circuit current is 1 Amp. With this current now known, we can calculate the voltage across each resistor.

Using Ohm's Law, write the equation for the voltage across the resistors:

For R1: $E = IxR$

For R2: $E = IxR$

For R3: $E = IxR$

Remember that we have to keep track of what we are applying Ohm's Law to. Looking at the above equations show that we need the individual currents through the resistors, but we calculated total circuit current. Do you remember the special relationship of current in a series circuit? All components in a series circuit pass the same amount of current.

$$I_{circuit} = I_{R1} = I_{R2} = I_{R3}$$

If we substitute the total current for the individual currents and substitute in the values of the resistors, we can calculate the voltage across each resistor.

For R1: $E = I_{circuit}xR = 1A\ x\ 2\Omega = \mathbf{2V}$

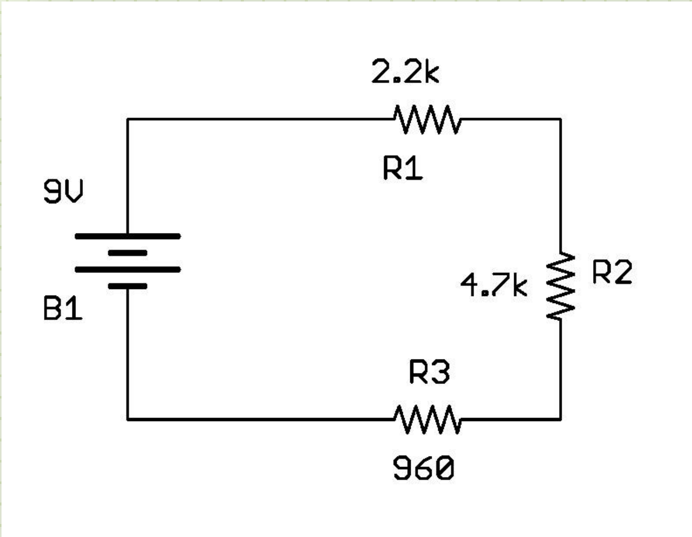
For R2: $E = I_{circuit}xR = 1A\ x\ 3\Omega = \mathbf{3V}$

For R3: $E = I_{circuit}xR = 1A\ x\ 5\Omega = \mathbf{5V}$

What do these voltages mean? For a power supply, voltage is the pumping power that moves electrons through a circuit. For resistors, it is the dropping of this electron pressure across them. We refer to these voltages as **voltage drops** because the voltage in the circuit literally drops down to a new level after passing through a resistor. If the battery is seen as adding voltage, these resistors can be viewed as removing voltage.

Kirchhoff's Voltage Law

You may have noticed something about those voltages calculated above. The resistor voltages all add up to the supply voltage. Through our calculations, we have stumbled upon another electronic Law. **Kirchhoff's Voltage Law** states that the sum of all the voltages in a closed path will equal zero. Since our power supply raises the circuit voltage by 10 Volts and the resistors drop the voltage by 10 Volts total, we have a net 0 Volts, which is exactly what Kirchhoff's Law states. Let's do one more example but this time, instead of my white board sketch and easy values for resistors, we'll look at a more realistic schematic and more common resistor values. This will force you to have to convert values with multipliers.



There are a couple of things of note in this schematic. First, note the symbol for the battery. It looks like two symbols on top of each other. That is because it is. The symbol we have been using is technically the symbol for a single cell (like one AA or AAA battery). You have probably noticed that most of the devices you have used take more than one battery. This is because a single AA battery only produces 1.5V. Most circuits require higher voltages to work so we hook up multiple batteries in series. Just like resistor voltage drops add up to drop the supply voltage, the supply voltage adds up too. If I put four AA batteries in series, I wind up with a total voltage of 6V. So the schematic is showing that our 9V battery is actually comprised of two cells. Second, the Ohm symbol (Ω) has been dropped from the resistor values. This is a common practice on schematics. The drafters assume the viewer would know what units the values are in so they omit them from the schematic which often leads to better readability. So R3 is 960Ω and R2 is 4.7kΩ or 4700Ω. Remember, we want to have all values in the base units when we plug them into Ohm's Law so we get base units out. Let’s proceed as before to get the total circuit current.

For the Circuit: $$I = \frac{E}{R}$$

Again, we know we have the total circuit voltage, but we don't have the total circuit resistance. Let's calculate it.

$$R_{Total} = R_1 + R_2 + R_3 + \cdots$$

$$R_{Total} = 2200\Omega + 4700\Omega + 960\Omega = \mathbf{7860}\Omega$$

Note that we added the resistor values in base units (Ω) to get an answer in base units. Now that we have circuit resistance, we can calculate total current.

For the Circuit: $$I = \frac{E}{R} = \frac{9V}{7860\Omega} = 0.00114504A = \mathbf{1.15}\boldsymbol{mA}$$

Here we see a few things at work. First, we made sure we used base units in the equation (V and Ω) so that we got base units (A) out. Then, we wanted to express the answer in a more convenient form so we converted the answer to mA. Lastly, we rounded the answer to three significant figures. It is good to round final answers but keep in mind, using rounded numbers in calculations removes some precision to your final answers. As you work problems out yourself, write down the full results on your paper so if you need that value again you will have the most precise value to continue calculations.

Now that we have the current, and remembering that the system current is the same current through the whole circuit, we can calculate the individual resistor voltage drops.

For R1: $E = IxR = 0.00114504A\ x\ 2200\Omega = 2.51908V = \mathbf{2.52V}$

For R2: $E = IxR = 0.00114504A\ x\ 4700\Omega = 5.38168V = \mathbf{5.38V}$

For R3: $E = IxR = 0.00114504A\ x\ 960\Omega = 1.099236V = \mathbf{1.10V}$

And just to make Kirchhoff happy, let's add all of these voltage drops together.

$$2.52V + 5.38V + 1.10V = \mathbf{9V}$$

The resistors drop the same voltage that the battery supplies. The total voltage added equals the total voltage consumed so the all the voltages sum to zero. That is exactly what Kirchhoff's Voltage Law states.

Well this is all very interesting but does this stuff really work. Let's head into the Lab and see if FRED can confirm these readings.

MOD 2: LAB

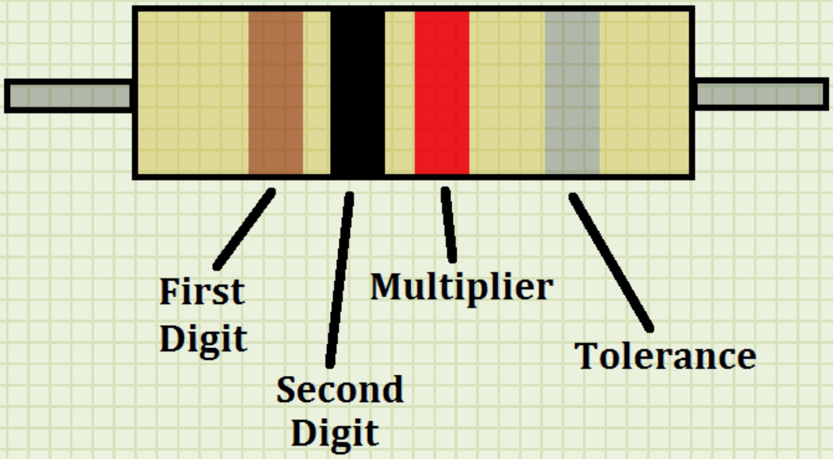
Welcome to the MOD2 Lab! In this lab we will use FRED to supply voltage to a circuit we create, do calculations predicting voltages across the components, and use FRED to actually measure those voltages to ensure we are correct. But first, we need to learn how to read the values of resistors.

Resistor Color Code

You may have noticed that the resistors included in your lab kit have colored bands around them. Pretty as they may be, these bands actually represent the values of these resistors. Resistors can have a varying number of bands, but the scheme for using them is pretty standard. It is important to note that resistors come in many different shapes, sizes, values, and functions. We are going to only cover the color code for standard axial leaded carbon resistors (like the ones in your kit).

Resistors normally come in a 4-band or 5-band configuration. If you look at one of the resistors in your kit, you will see 4 distinct bands of color. If you look close, you may even see a larger gap between the set of 3 bands and the single band. Sometimes you can make it out, sometimes you can't. Let's look at what these bands represent.

First, we will look at the 4-band resistor. The picture below shows a typical band layout. On this resistor, 3 of the bands are close together and one is separated from the bunch. The group of three bands represents the VALUE of the resistor (its resistance) and the fourth band is the TOLERANCE. The tolerance is a measure of how much the actual resistance of the resistor can vary from the designated value shown on the bands. Resistors are fabricated many different ways and it leads to some variance in their values. Temperature also has an effect on resistors. The tolerance band tells circuit designers how off the resistance might be so the designer can analyze her circuit for best and worst case conditions to ensure the device will operate over the range of resistances. For many applications of resistors, being off by even 10% doesn't have a large impact on the function of the circuit. But for other applications, resistance is vital and low tolerance resistors must be used.



Looking at the three bands that represent value, there are two bands that are significant digits and the third band is a multiplier. The chart below shows what numbers these colored bands represent.

Color	Value	Multiplier		Tolerance
Black	0	10^0	1	
Brown	1	10^1	10	±1
Red	2	10^2	100	±2
Orange	3	10^3	1,000	
Yellow	4	10^4	10,000	
Green	5	10^5	100,000	±0.5
Blue	6	10^6	1,000,000	±0.25
Violet	7	10^7	10,000,000	±0.1
Gray	8	10^8	100,000,000	
White	9	10^9	1,000,000,000	
Gold		10^{-1}	0.1	±5
Silver		10^{-2}	0.01	±10
None				±20

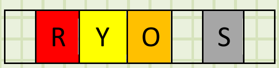
The 4-band resistor will only have a Tolerance of Gold, Silver, or none.

So if we put together the resistor above (Brown/Black/Red with Silver tolerance) we would construct the value by taking the first two bands and writing them down and then multiplying the correct multiplier. This will give us the value of the resistor:

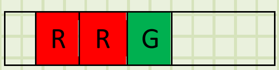
$$\frac{1}{Brown}\frac{0}{Black}\frac{x100}{Red} = 1000\Omega \; or \; \boldsymbol{1k\Omega \; with \; tolerance \; \pm 10}$$

You can use a quick helper rule when you figure out the value. Write down the first two digits and then use the third band to tell how many zeros to add to it. From the above example, you would write 10 and then the red band tells you to add two zeros. The final result is 1000.

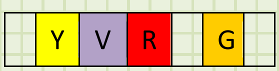
Accounting for the tolerance (±10%), that means the resistor may be actually valued from 900 to 1100 ohms. Figure out the following resistor values. In case the colors are hard to read or you printed a B&W copy of this manual, I have put the letter representing the color in the band also.



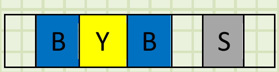
Value __________________ Tolerance __________



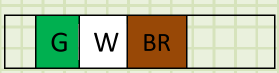
Value __________________ Tolerance __________



Value __________________ Tolerance __________



Value __________________ Tolerance __________



Value __________________ Tolerance __________

1. Red/Yellow/Orange = 2 4 000 = 24000Ω or **24kΩ ±10%**

2. Red/Red/Green = 2 2 00000 = 2,200,000Ω or **2.2MΩ ±20%**

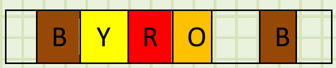
3. Yellow/Violet/Red = 4 7 00 = 4700Ω or **4.7kΩ ±5%**

4. Blue/Yellow/Blue = 6 4 000000 = 64,000,000Ω or 64**MΩ ±10%**

5. Green/White/Brown = 5 9 0 = **590Ω ±20%**

How did you do?

Five band resistors work just like four band resistors except they have an extra digit band. They will have three significant figures and a multiplier. It works the same way though. Just write down the first THREE numbers and then use the multiplier to add the right number of zeros.

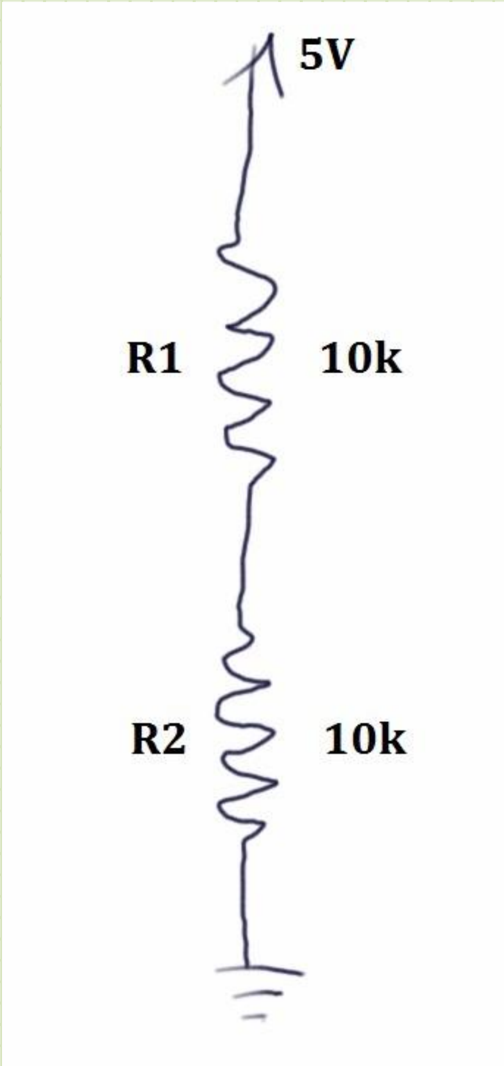


Brown/Yellow/Red/Orange = 1 4 2 000 = 142,000Ω or **142kΩ ±1%**

The 5-band resistor will always use a tolerance band (there is no "none" option) and it will be Brown, Red, Green, Blue, or Violet. These resistors tend to have fabrication methods that allow them to have higher precision.

Series Circuit 1

So let's do this. Below is a circuit that you will create on the breadboard. But for now, let's calculate the voltages across the resistors. We will then use FRED to confirm these values.



I am showing the circuit in a new form you haven't seen yet. It replaces the battery with representations for its positive and negative terminals. The arrow at the top is the symbol for a power supply. It is labeled with the voltage present at the supply (5V in this case). The three lines drawn at the bottom of the circuit is called **ground**. Ground is a reference point in the circuit. It is normally the negative side of the battery, but it doesn't have to be. This way of drawing the circuit makes it easy to visualize the voltage drops across the resistors so we will use it for this lab.

Like the previous circuits, in order to figure out the voltages across the resistors, we will need to calculate the current through them. And in a series circuit, the circuit current is the same as the current going through any of the components. So the first step is to calculate the total circuit current.

So go ahead and calculate the total circuit current. Here is a reminder of the formulae you will need.

For the Circuit: $I = \frac{E}{R}$

$$R_{circuit} = R_1 + R_2$$

When I do the calculation, I get the following:

$$R_{circuit} = R_1 + R_2 = 10k\Omega + 10k\Omega = \boldsymbol{20k}\Omega$$

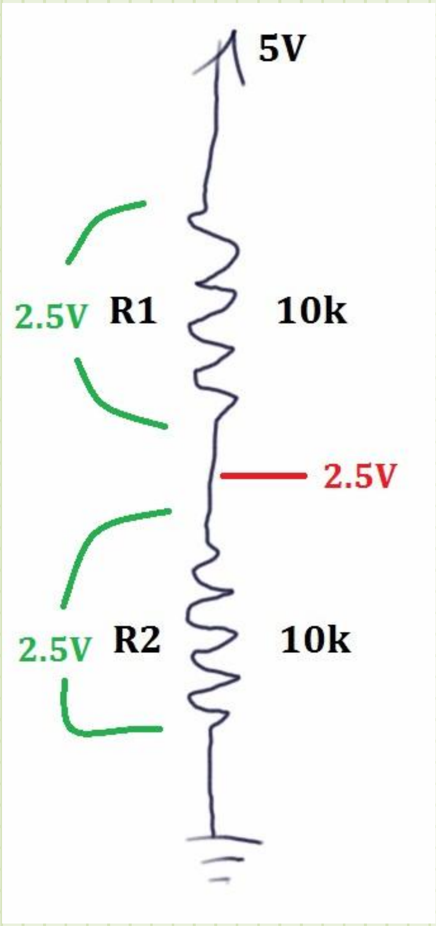
For the Circuit: $I = \frac{E}{R} = \frac{5V}{20000\Omega} = 0.00025A \ or \ \mathbf{0.25mA}$

Now, calculate the voltages across the resistors.

For R1: $E = I \ x \ R = 0.00025A \ x \ 10000\Omega = \mathbf{2.5V}$

For R2: $E = I \ x \ R = 0.00025A \ x \ 10000\Omega = \mathbf{2.5V}$

It shouldn't surprise us to see that two identical resistors with identical currents should produce identical voltage drops.



If you look at our schematic, you can label the voltage drops across the resistors. If you start at the 5V power supply and start heading through the circuit the first thing you will run into is R1. R1 drops the circuit voltage by 2.5V leaving 2.5V left at the junction of R1 and R2 (labeled in Red). Then, the current runs down to R2 where it also drops the voltage by 2.5V. We end up at the ground with a voltage of 0V. Since this is the negative terminal of the battery, the battery adds 5V to our circuit and we are back at the top of the circuit and 5V again. We will now set this circuit up on the breadboard. We will use the 5V supply from FRED to be our voltage source. We will hook up two 10kΩ resistors in series, and we will use FRED's voltage detector to show the voltage across R1 (which should be 2.5V) and across R2 (which should be 2.5V).

Objective:

In this lab you will create a circuit and verify voltages are as predicted by Ohm's Law.

Materials:

FRED, two 10kOhm resistors, hook up wires, breadboard.

Procedure:

1. Power on FRED and press RST to ensure a clean boot up.

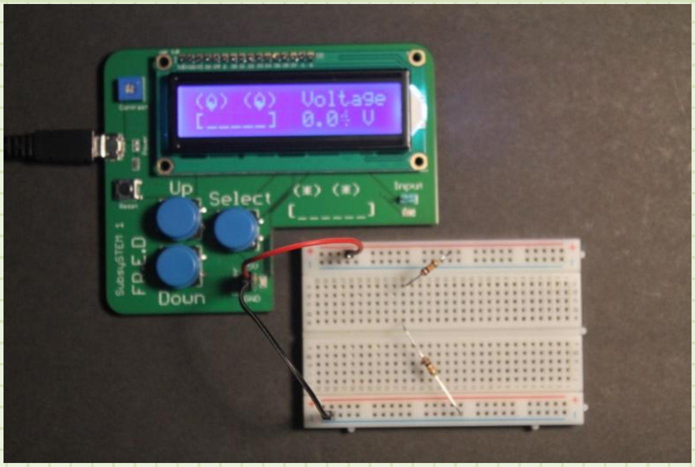
2. When FRED is ready (displays the Main Menu prompt) use the Down navigation button to get to the MOD 2 menu selection and press Select.

3. FRED will show up on the left of the screen and a volt meter will be displayed on the right. The meter will most likely be displaying rapidly changing voltages. This is normal when FRED is not connected to a voltage to read. With the input to FRED not connected, the voltage on that input tends to float around based on the internal condition of FRED and the status of power to him.

4. Hook up FRED's power supply to the breadboard:

> ***WARNING: Never directly connect the 5V and Ground connections of FRED directly together. This would cause the power supply on FRED to try to supply way too much current and could damage FRED or the device supplying power to FRED.***

a) Connect the Power Cable to the power header on FRED so the red lead is connected to the 5V side and the black lead is connected to the GND side.
b) Connect the Red lead from the Power connector to the upper Red breadboard power strip and the Black lead from the Power connection on FRED to the lower Blue power strip on the breadboard.



5. Select the two 10kΩ resistors. What should the color bands look like for this size resistance? The resistors supplied with your kit are of the four band type. That means the first three bands are the value. Try to come up with the color bands on your own and then we will review your choice.

Let's break apart the value we are looking for to see what resistor color sequence we need.

$$10k\Omega = 10000\Omega = \frac{1}{Digit1}\frac{0}{Digit2}\frac{000}{Multiplier}$$

$$\frac{Brown}{Digit1}\frac{Black}{Digit2}\frac{Orange}{Multiplier}$$

So a 10kΩ resistor with four bands should have the color sequence Brown/Black/Orange. Find those two resistors and hook them up as follows:

a. Connect the first resistor (R1 in our schematic) by placing one of the leads into the upper Red power strip of the breadboard and the other lead to hole 20a on the breadboard main area.
b. Connect the second resistor (R2) by placing one lead into hole 20e and the other into the lower Blue power strip on the breadboard.

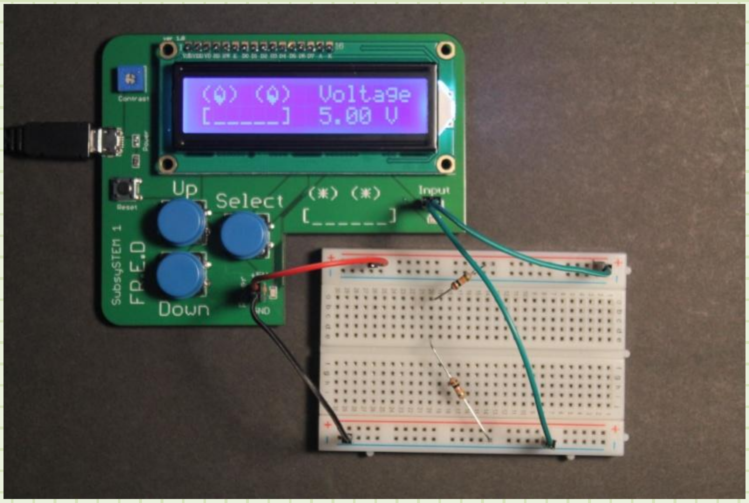
6. Take a moment to convince yourself that we have created a complete circuit for power from FRED to go through R1 and then R2 in series and return to FRED via the ground connection. Compare it to the schematic to see that it

is in fact what the circuit calls for. When you are satisfied continue to the next step.

7. Hook up the Test Cable to FRED's Input port. These cable wires are now connected to the input of FRED's voltage meter. When you want to test the voltage across a component, you just connect one of the jumpers to one side and the other to the other side of the component.

Referring to our circuit, let's take the voltages available to us.

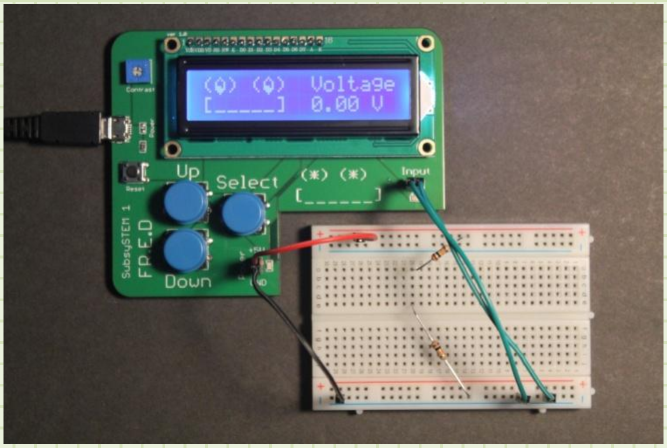
8. Verify the power supply. Attach one of the input jumpers to the upper Red power strip and the other jumper to the lower Blue power strip on the breadboard. Record the voltage displayed by FRED.



$$Voltage_{Input} = \_\_\_\_\_\_\_$$

You should see really close to 5V. This is the power coming from FRED. He does his best to regulate this voltage at exactly 5V, but may be off a little for various reasons.

9. Let's verify that our ground is in fact at 0V. Move the input jumper from the upper Red to the lower Blue power strip on the breadboard. Record you result:

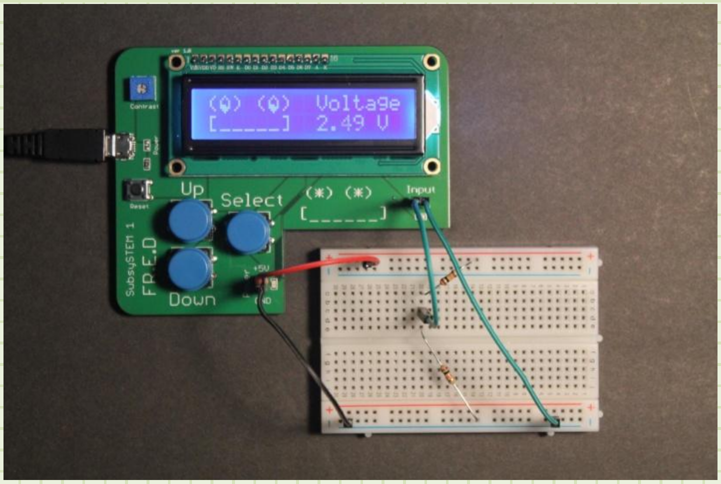


$$Voltage_{Ground} = \_\_\_\_\_\_\_\_$$

You should see zero, or really close to zero volts.

If you did not get these results, check your connections carefully.

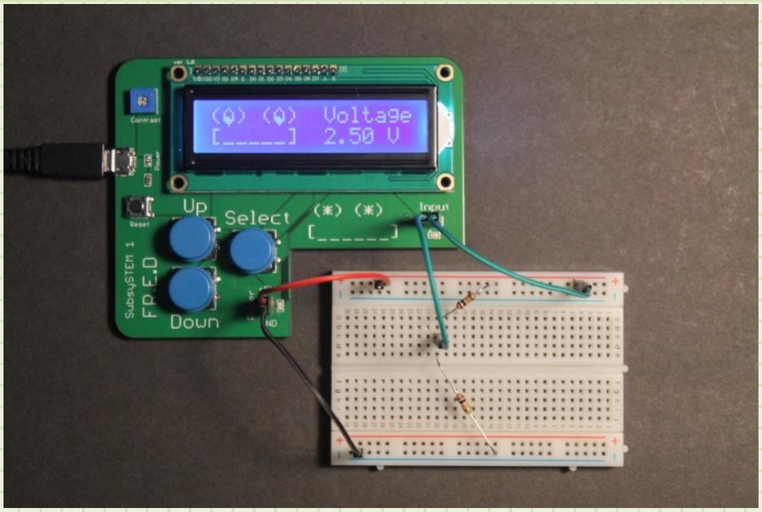
10. Now let's move the input jumpers to measure voltage across R2. Move one of the input jumpers from the lower power strip to the junction of our two resistors. You can do this by placing the input jumper into hole 20c. What voltage is displayed on FRED? Does it look familiar? Record the voltage.



$$Voltage_{R2} = \_\_\_\_\_\_\_\_$$

Note that I labeled the voltage with respect to R2. When you see where we are sampling the voltage from, you can see that it is a measurement of the voltage across R2 itself. We previously calculated what this voltage should be. Our calculations based on Ohm's Law predicted a voltage of 2.5V. What do you think? Did we nail it? FRED should have reported a voltage really close to 2.5V. Remember that resistors have tolerances associated with them so you may not read 2.5V exactly, but it should be really close.

11. Now we want to measure the voltage across R1. We already have an input jumper at the bottom of R1. Move the input jumper connected to the lower Blue power strip to the upper Red power strip. This puts our input jumper wires at the top and bottom of R1 which will allow us to read the voltage across that component. Record the voltage.



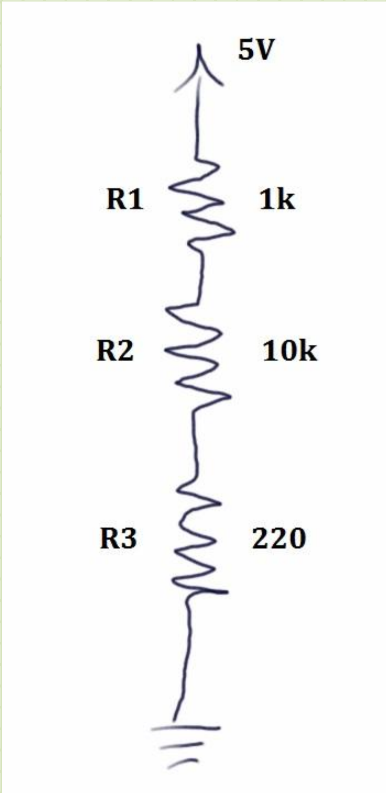
$$Voltage_{R1} = \_\_\_\_\_\_\_\_$$

Did you get 2.5V? That is what we calculated it should be. What's more, if you add the two resistor values together, you get 5V which is what is supplied to the circuit. So what the power supply provides, the circuit consumes and the net voltage is zero. This, again, confirms Kirchhoff's voltage law.

Let's try a more complicated circuit by adding a resistor and having all three resistances different.

Series Circuit 2

The below circuit is a series circuit with three resistors that all have a different value. We still have the same supply from FRED (5V). Now, the current will leave the positive supply, head down through R1, drop voltage, the current will continue down through R2, drop more of the voltage, and finally go through R3 and drop the remaining voltage to get to 0V at our ground. From there it enters the power supply which raises the circuit voltage back up to 5V and the current continues to flow in this path. As before, we want to calculate these voltages based on Ohm's Law and then test them to prove they work. At this point, you have all the knowledge to solve this circuit for the voltages across each of the resistors. Try that now by yourself before I show you how I solve for them. Feel free to refer back to your notes and the previous problems for help and to remember the equations we used. Record your results so we can refer back during the lab.



For R1: $E =$ __________

For R2: $E =$ __________

For R3: $E =$ __________

To solve this circuit, I will proceed as before:

$$R_{circuit} = R_1 + R_2 + R_3 = 1k\Omega + 10k\Omega + 220\Omega = \mathbf{11220}\Omega$$

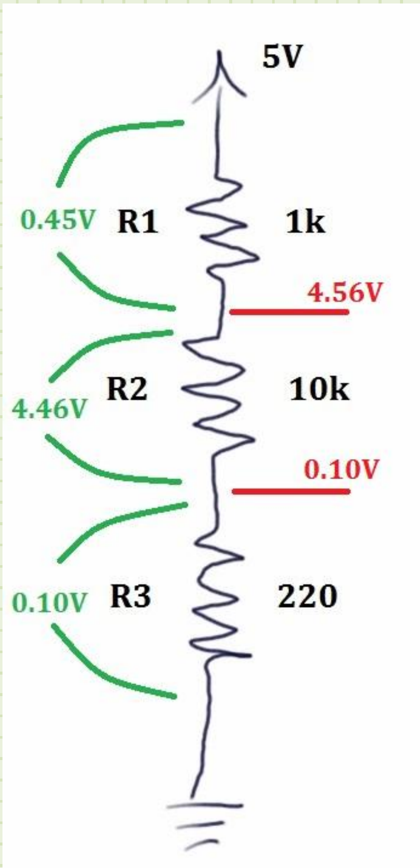
For the Circuit: $$I = \frac{E}{R} = \frac{5V}{11220\Omega} = 0.0004456A \;\; or \;\; \mathbf{0.45mA}$$

Now, calculate the voltages across the resistors.

For R1: $E = I\ x\ R = 0.0004456A\ x\ 1000\Omega = \mathbf{0.45V}$

For R2: $E = I\ x\ R = 0.0004456A\ x\ 10000\Omega = \mathbf{4.46V}$

For R3: $E = I\ x\ R = 0.0004456A\ x\ 220\Omega = 0.098V = \mathbf{0.10V}$



If we transfer these voltages to our schematic, you can see the resulting drops across the resistors and predict what voltages we should see as we probe this circuit. When we test the power supply as before, we should see 5V at the top of R1 and 0V at the bottom of R3. We should see the calculated voltages across each resistor. We will also take voltages at the resistor junctions with respect to ground (one of the input probes in the lower Blue power strip). At the junction of R2 and R3 we should see 0.10V. This is because this point is 0.10V above ground (our reference point). At the junction of R1 and R2 we should see 4.56V. Right? You may be asking "Don't you mean 4.46V?"

Always remember that voltage is always a difference of potential between two points. Since our reference for this measurement is ground (at 0V), we have to look at what voltage to expect at the junctions with respect to ground. You can see that when I measure the voltage at the junction of R1 and R2 with respect to ground, I am actually reading the voltage across R2 and R3. So my expected voltage has to be the combination of the 0.10V voltage of R3 and the 4.46V across R2. That's how we get to expecting 4.56V when we probe that junction. You will see this in action.

Objective:

In this lab you will create a circuit and verify voltages are as predicted by Ohm's Law.

Materials:

FRED, three resistors (220Ω, 1kΩ, and 10kΩ), hook up wires, breadboard.

Procedure:

1. Power on FRED and press RST to ensure a clean boot up.

2. When FRED is ready (displays the Main Menu prompt) use the Down navigation button to get to the MOD 2 menu selection and press Select.

3. FRED will show up on the left of the screen and a volt meter will be displayed on the right.

4. Hook up FRED's power supply to the breadboard:

> ***WARNING: Never directly connect the 5V and Ground connections of FRED directly together. This would cause the power supply on FRED to try to supply way too much current and could damage FRED or the device supplying power to FRED.***

a) Connect the Power Cable to the power header on FRED so the red lead is connected to the 5V side and the black lead is connected to the GND side.
b) Connect the Red lead from the Power connector to the upper Red breadboard power strip and the Black lead from the Power connection on FRED to the lower Blue power strip on the breadboard.

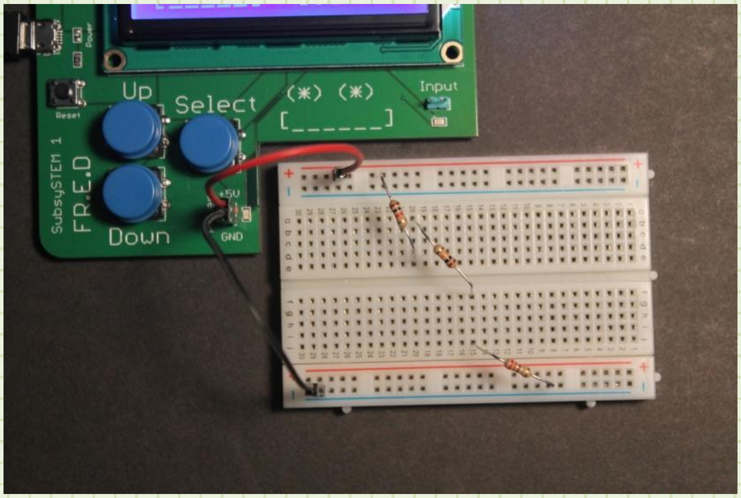
5. Select the resistors based on their color bands.

220 (Red/Red/Brown)
1k (Brown/Black/Red)

10k (Brown/Black/Orange)

Connect the three resistors as follows:

a. Connect the 1k resistor (R1 in our schematic) by placing one of the leads into the upper Red power strip of the breadboard and the other lead to hole 20e on the breadboard main area.
b. Connect the 10k resistor (R2) by placing one lead into hole 20a and the other into 15f.
c. Connect the 220Ω resistor (R3) by placing one lead into hole 15j and the other into the lower Blue power strip (ground).



6. As before, take a moment to convince yourself that we have created a complete circuit for power from FRED to go through R1, R2, and then R3 in series and return to FRED via the ground connection. Compare it to the schematic to see that it is in fact what the circuit calls for. When you are satisfied continue to the next step.

7. Hook up the Test Cable to FRED's Input port. These cable wires are now connected to the input of FRED's voltage meter.

Referring to our circuit, let's take the voltages available to us.

8. Verify the power supply. Attach one of the input jumpers to the upper Red power strip and the other jumper to the lower Blue power strip on the breadboard. Record the voltage displayed by FRED.

$$\boldsymbol{Voltage_{Input}} = \_\_\_\_\_\_\_\_$$

You should see really close to 5V. This is the power coming from FRED.

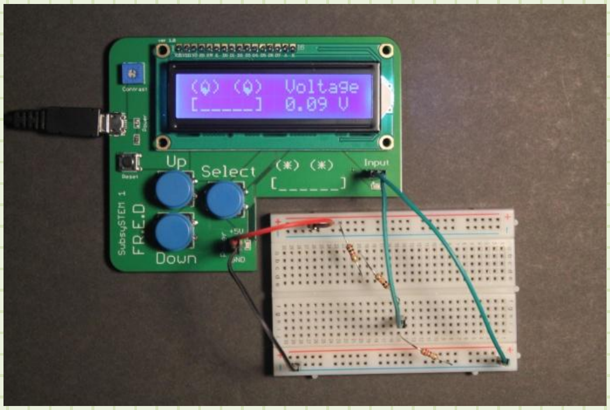
9. Let's verify that our ground is in fact at 0V. Move the input jumper from the upper Red to the lower Blue power strip on the breadboard. Record you result:

$$\boldsymbol{Voltage_{Ground}} = \_\_\_\_\_\_\_\_$$

You should see zero, or really close to zero volts.

If you did not get these results, check your connections carefully.

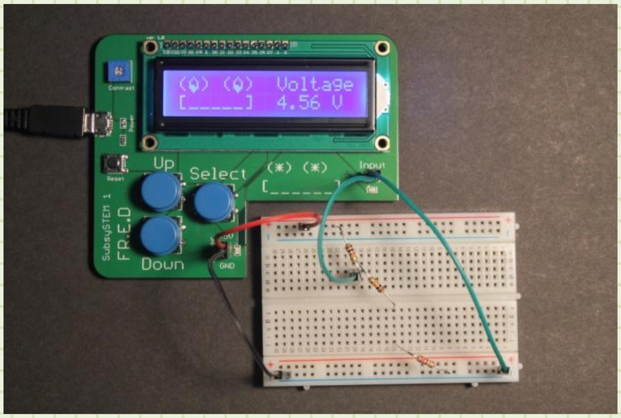
10. Now let's move one of the input jumpers from the lower power strip to the junction of resistors R2 and R3. You can do this by placing it into hole 15h. Record the voltage.



$$\boldsymbol{Voltage_{R3}} = \_\_\_\_\_\_\_\_$$

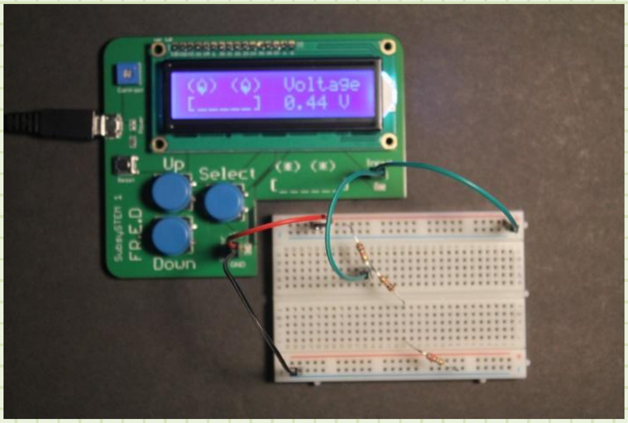
Again, I labeled the voltage with respect to R3. When you see where we are sampling the voltage from and you know that it is with respect to ground, you can see that it is a measurement of the voltage across R3 itself. We previously calculated what this voltage should be. Our calculations based on Ohm's Law predicted a voltage of 0.10V. FRED should have reported a voltage really close to this. Remember that resistors have tolerances associated with them so you may not read 0.10V exactly, but it should be really close.

11. Now let's move the input jumper to the junction of R1 and R2 in our schematic. Do this by placing the jumper wire in hole 20c. FRED is now displaying the sum of the voltages across R2 and R3 and it should be close to our prediction of 4.56V. Record the voltage.



$$Voltage_{R2+R3} = \_\_\_\_\_\_\_\_$$

12. Now, move the input jumper in the lower Blue power strip to the upper Red power strip. This has our input jumpers on either side of R1. Record the voltage. We calculated 0.45V.



$$Voltage_{R1} = \_\_\_\_\_\_\_\_$$

Conclusion

We covered a ton of material in this module. Let's look at some highlights:

1. Resistor color bands report their resistance values and their tolerance. They could be 4 band or 5 bands depending on the manufacturing process. A 4 band resistor may look like a 3 band resistor if it omits the tolerance band. If this is the case, the tolerance is ±20%.

2. Ohm's Law allows us to analyze a circuit mathematically before we ever construct it. We used it to calculate current and voltage drops in our series circuits.

3. Kirchhoff's Voltage Law tells us that all of the voltages in a closed loop must sum to zero. We see this when we understand that the battery injects positive voltage into our circuit and then the resistors drop that voltage back down. The net in our calculations always showed this balance.

4. Current through a series circuit is the same for all components in that circuit.

5. The voltage drop across each resistor can be calculated if the current and resistance values are known.

6. We learned that you can combine resistors in series into a single equivalent resistor by just adding their values together.

7. We learned that current can be considered to be the movement of negative charges through a circuit (electrons) or the movement of positive charges through a circuit ("holes").

8. We learned how to create our own conversion factors to be able to convert our measurements into more convenient units.

9. We showed different ways a schematic diagram may look and the symbols we expect to see in them for the components we used.

10. We took actual readings of voltages in our circuits to confirm our calculation results.

11. We learned that directly connecting the positive and negative power terminals together could cause severe damage to equipment.

There is a lot more to come. In the next module, we will discuss a second type of circuit and its particular analysis methods. Prepare for the **Parallel Circuit**.

Module

3

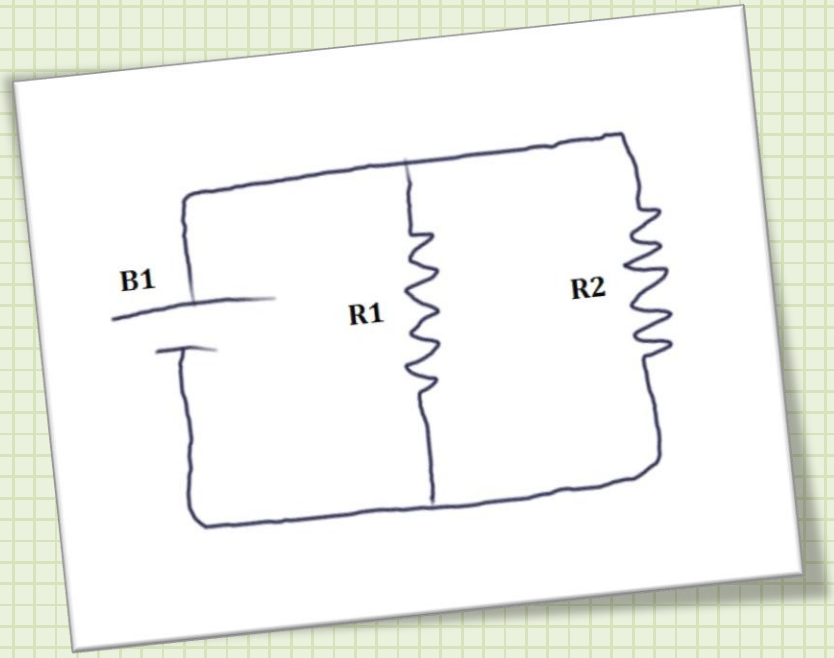
MOD3: Parallel Circuits

In the series circuit, current was the same through all components in the circuit. It followed one unbroken path through all the components. Those components dropped voltage proportional to their resistance values. But what if we needed the voltage across components to remain constant? Think about the power coming from the power outlets in your house. If these were part of a series circuit, we would have two big problems. The first is that every outlet would need something plugged into it. If you remember from the series circuits, if we opened the circuit at any point, all current would stop. The second problem is that the voltage would be divided up among all of the things plugged in. This would leave too low a voltage for many things to even operate. Fortunately, there is a way to supply the house so that every outlet sees the same voltage regardless of how many things are plugged in. This type of circuit is called a **parallel circuit**.

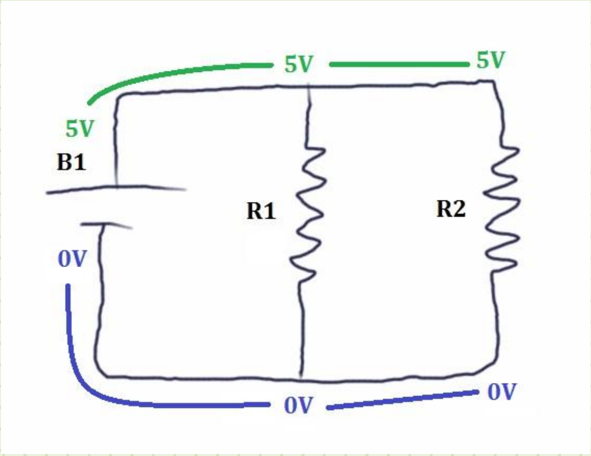
A parallel circuit will appear to be the opposite of a series circuit. Look at the below table to see what I mean.

	Current	Voltage
Series Circuit	Current is equal through each component	Voltage is different across each component
Parallel Circuit	Current is different through each component	Voltage is equal across each component

The Parallel Circuit



Unlike the series circuit, as current leaves the battery it comes to a fork in the road. The current then divides and some goes through R1 and some goes through R2. The two individual currents then recombine to enter the battery. That means that there will be multiple current paths in my circuit. The other thing to recognize is that the top of the battery (the positive terminal) and the top of R1 and R2 are all at the same potential. They are connected by a wire and we have stated that a wire has no resistance and so, cannot drop any voltage. The same is true of the negative terminal and the bottom lead of both resistors.



The picture at left shows this distribution of voltage across the circuit. Because of this configuration you can see that all of the components in parallel have the same voltage across them. Each resistor has

5V on one side and 0V on the other. This is the advantage of the parallel circuit and why your house is wired this way. As I continue to add components in parallel, I do not change the voltage across the existing components and I have the full supply voltage across the added component. These facts will be used to help calculate the desired parameters of this circuit. Looking again at this circuit, can you figure out how to calculate the current through the resistors? When you hear "calculate current," your mind should go to Ohm's Law.

$$I = \frac{E}{R}$$

And if we tailor this to the resistors, we get:

For R1: $I = \frac{E}{R}$

For R2: $I = \frac{E}{R}$

Because we know that the voltages in a parallel circuit are all equal we get:

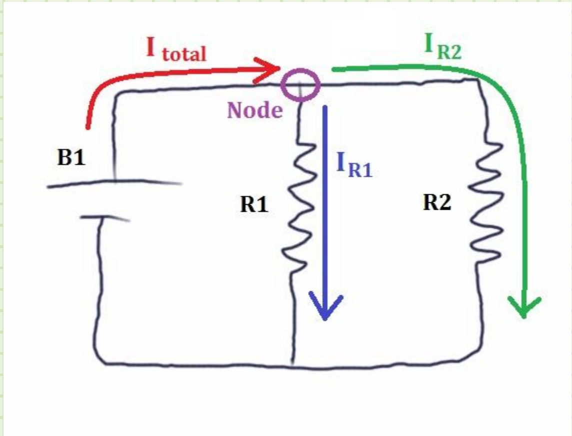
$$E_{Supply} = E_{R1} = E_{R2}$$

So if we know the supply voltage and individual resistance values, which we most often do, then we can quickly determine the current through each component (in this case, R1 and R2).

That will give us the current though each branch of the parallel circuit, but what about total circuit current? Our old friend Kirchhoff is going to make reappearance.

Kirchhoff's Current Law

Kirchhoff has a voltage rule but also has a current rule. He looked at all the nodes in a circuit. A node is just a place in our circuit where multiple paths for current exist. He looked at the nodes and made the observation that the amount of current entering any node must equal the amount of current leaving that node. This is **Kirchhoff's Current Law**.



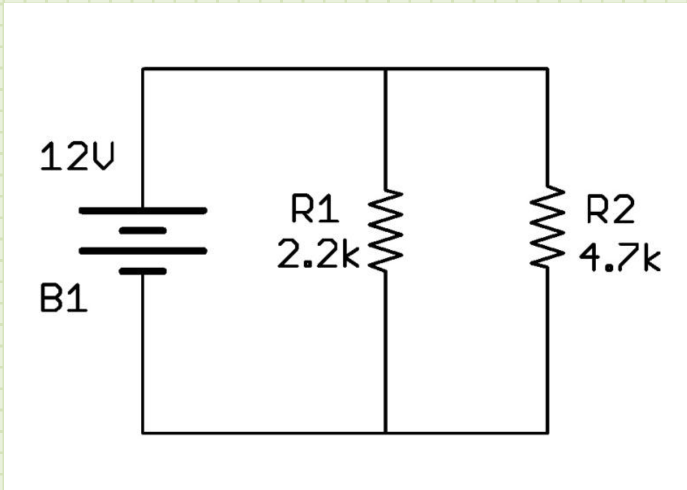
The circle (purple) is one of the nodes in this circuit. It is a connection point between the power supply and the two resistors. Current from the power supply (Red line) flows into the node and two currents exit. One is the current that flows through R1 (the Blue line) and the other is the current that flows through R2 (the Green line). Kirchhoff's Current Law states that sum of the currents entering a node must equal the sum of the currents leaving that node. Let's write that as an equation for the above node.

$$I_{total} = I_{R1} + I_{R2}$$

Since we already have shown how to solve for the individual circuit currents, we see now that we can just add them together to get the total circuit current. Let's walk through a circuit and do these calculations.

Parallel Circuit 1

We'll start with the below circuit. Let's determine the voltages and currents in all the components.



The first thing to recognize is that we have a parallel circuit with the power supply, R1, and R2 all in parallel with each other. Based on what we know about a parallel circuit, we can immediately state that the voltages across each component are the same and are equal to the supply voltage.

$$E_{supply} = E_{R1} = E_{R2} = 12V$$

Wow, that was easy. Remember what we had to go through to find the voltages in the series circuit?

Now let's calculate the currents through the resistors.

For R1: $$I = \frac{E}{R} = \frac{12V}{2200\Omega} = 0.0054545A = \mathbf{5.45\ mA}$$

For R2: $$I = \frac{E}{R} = \frac{12V}{4700\Omega} = 0.0025532A = \mathbf{2.55\ mA}$$

Finally, let's find the total circuit current:

$$I_{total} = I_{R1} + I_{R2} = 0.0054545A + 0.0025532A = 0.0080A = \mathbf{8.0\ mA}$$

So, 8 mA of current leaves the battery and moves to the resistors. At the R1 branch, 2.55 mA breaks off and heads through R1 while the remaining 5.45 mA heads through R2. The currents combine back up at the bottom of R1 and are 8 mA again which head into the battery and the circuit is complete.

There is actually another way to solve this circuit for total current. Let's look at the Ohm's Law equation to solve for total circuit current.

For the Circuit: $I = \frac{E}{R}$

We have the total circuit voltage, but we don't have the total circuit resistance. Or do we?

Combining Resistors in Parallel

Remember that we discussed combining resistors in series. One of benefits of a series circuit was that it was easy to do this. The total circuit resistance is just the sum of the resistors. This gave us an equivalent circuit resistance. Parallel resistors can be combined also. It just takes a little more algebra. The equation for combining resistors in parallel is:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

So in a parallel circuit, we use the above formula to combine resistors into an equivalent resistor. Let's show how this works by solving for total current in the last circuit.

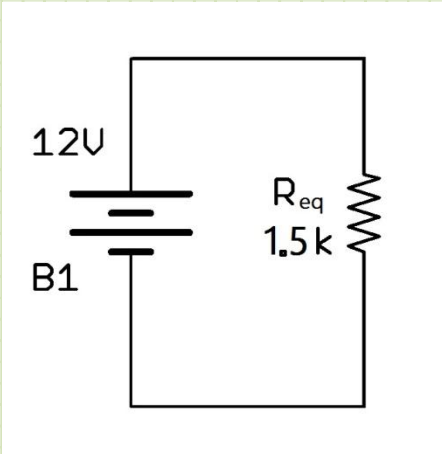
First, calculate the equivalent resistance of R1 and R2.

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{2200\Omega} + \frac{1}{4700\Omega} = \frac{1}{1500\Omega}$$

Notice that we are not done. We solved for $1/R_{total}$ so we need to take the reciprocal to get the final answer.

$$\frac{1}{R_{total}} = \frac{1}{1500\Omega} \quad therefore \;\; R_{total} = \mathbf{1.50\ k}\Omega$$

What this equivalent resistance means is that we can replace the parallel resistors in the circuit with this one equivalent resistance. The resulting circuit is shown below.



When we combine these two resistors into a single equivalent resistance, it results in a pretty easy circuit to analyze. We now have a single power supply and a single resistance. To calculate the total circuit current, we can just use Ohm's Law:

For the Circuit: $I = \frac{E}{R}$

If we substitute the values in this circuit, we get the following:

For the Circuit: $I = \frac{E}{R} = \frac{12V}{1500\Omega} = 0.0080A = \mathbf{8.0\ mA}$

That is the exact same number we got when we calculated the current through R1 and R2 and then added those currents together. As far as the power supply is concerned, it doesn't care whether it is supplying power to a 2.2k and 4.7k resistor in parallel or to one 1.5k resistor. This ability to combine resistors into simpler circuits is going to be the key in solving the combination series-parallel circuits we will discuss in the next module. So going forward, either method of determining total circuit current is valid. Sometimes the method we choose will depend on the given information of the problem. We did this problem with two parallel resistors but the same method could be used for any number of resistors.

Because of the nature of the parallel resistance equation, **the combined parallel resistances will always be less than the smallest resistor we use in the calculation**. This is a quick way to check to see if we did our math right. In the above example, we combined a 2.2k and 4.7k resistor to get a total of 1.5k. This value is less than the 2.2k (smallest resistor) so it passes our check.

Let's head into the lab to check out some parallel circuits.

MOD 3: LAB

Objective:

In this lab you will create a parallel circuit and observe the effects of current in each branch. You will calculate the current in each branch using Ohm's Law.

Materials:

You will need FRED, three red LEDs, three 220 Ω resistors, one 10 kΩ and one 100k resistor, hook up wires, and breadboard.

Procedure:

1. Power on FRED and press RST to ensure a clean boot up.

2. When FRED is ready (displays the Main Menu prompt) use the Down navigation button to get to the MOD 3 menu selection and press Select.

3. FRED will show up on the left of the screen and a volt meter will be displayed on the right.

4. Hook up FRED's power supply to the breadboard:

WARNING: Never directly connect the 5V and Ground connections of FRED directly together. This would cause the power supply on FRED to try to supply way too much current and could damage FRED or the device supplying power to FRED.

a) Connect the Power Cable to the power header on FRED so the red lead is connected to the 5V side and the black lead is connected to the GND side.
b) Connect the Red lead from the Power connector to the upper Red breadboard power strip and the Black lead from the Power connection on FRED to the lower Blue power strip on the breadboard.

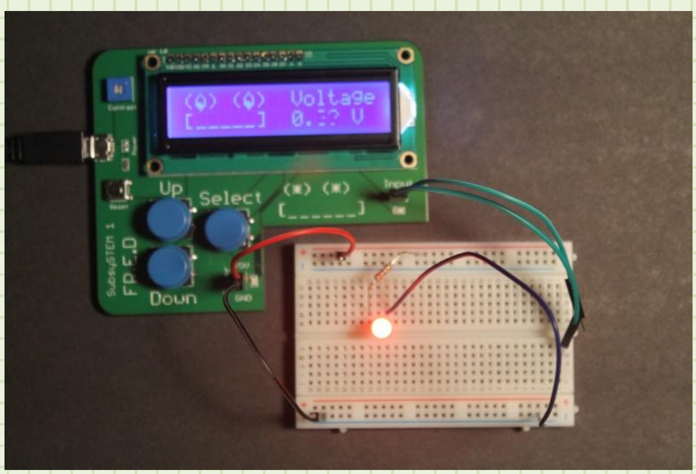
5. Select the 220 Ω resistor based on the color bands.

220 (Red/Red/Brown)

6. Place the resistor in the breadboard putting one lead of the resistor in the upper Red power strip and the other lead in hole 23d.

7. You have used an LED in the first lab when you completed a circuit with it. You also saw how hooking up the wrong way prevents current from going through it so you will need to be careful to hook up the LEDs in the correct direction to make these circuits. LEDs light when they are placed in a circuit and given enough voltage. As current through them increases, the intensity of light increases. This makes these devices current-sensing devices in a way and we are going to see this in action in this lab. First, let's start with hooking our LEDs in a series. Take one of the LEDs and locate the longer lead. That is the positive lead. Place it in hole 23e. Place the other lead (the negative lead) into hole 21e. We are starting to build a circuit where the current goes from the 5V supply from FRED, through the 220 Ω resistor, and then through the LEDs.

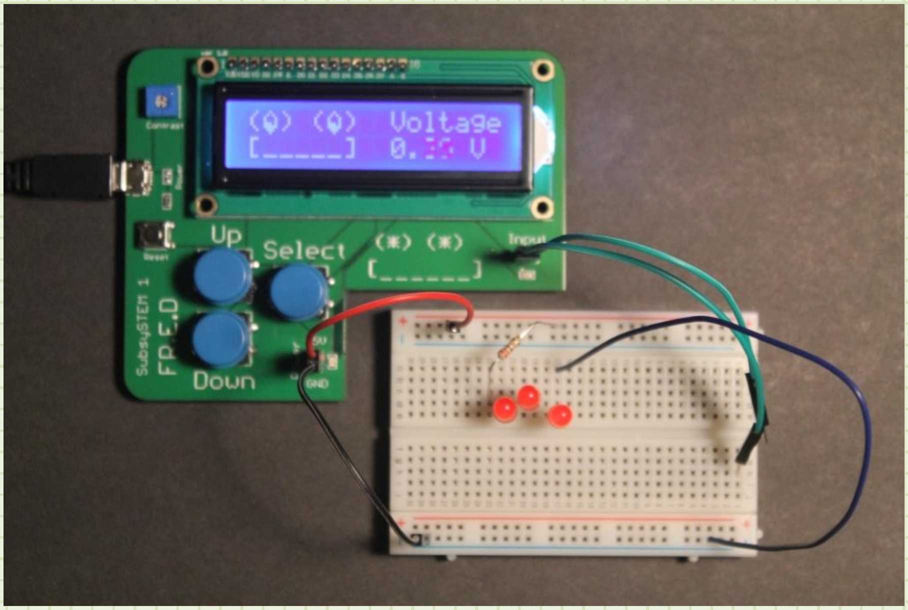
8. Now, take a jumper wire and connect it from hole 21d to the lower Blue power strip. The LED is lit. You completed a circuit from the positive supply, through the resistor and the LED, to the negative supply. It now allows current to flow through the LED. Now, let's hook up a second LED and see what happens.



9. Remove the jumper end installed in hole 21d and move it to hole 19b. Take the second LED. Locate the positive lead (the longer one) and insert it in hole 21d. Place the other lead in hole 19d. You now have a completed circuit through the 2 LEDs and they are lit. It may be hard to tell, but they are not lit as bright as the single LED. You can move the jumper between holes 19b and 21b to see if you see it.

10. Let's add another LED. Move the end of the jumper from hole 19b to 17b. Take the third LED and place the positive lead into hole 19e and the negative lead into hole 17e. This completes the circuit with the three LEDs. Now, you should definitely see a difference. The three lights are on, but they are much dimmer than before. Every time we add more components to a series circuit, the current decreases. The LEDs show this by lighting dimmer than before.

The other thing to notice is that the LEDs should all look like they are about the same brightness. Why is this?



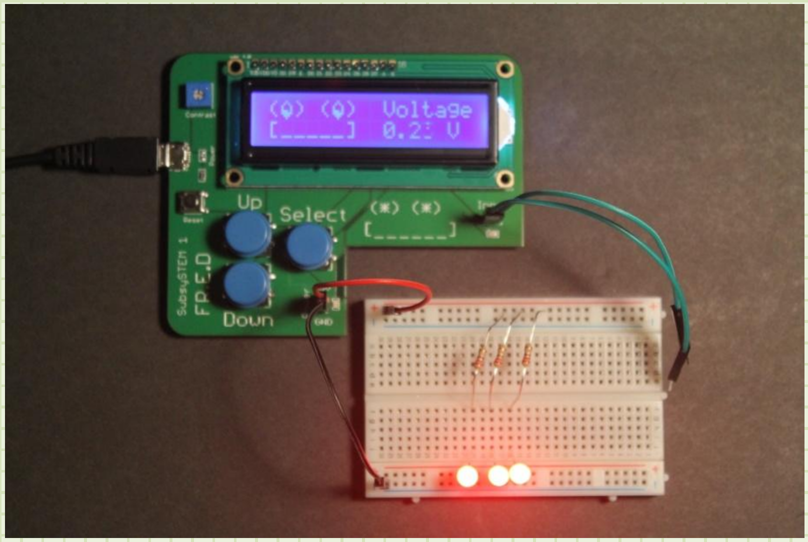
We discussed in MOD 2 (Series Circuits) that one of the characteristics of a series circuit is that the current through all the components in the series circuit is the same. If this is true, and LEDs vary their brightness based on the current flowing through them, then all the LEDs should glow with the approximately the same brightness. And they do. Now pick an LED and remove it from the breadboard. What happens? All three of the LEDs extinguish. A series circuit is one complete loop. If you break it anywhere, current in the whole circuit stops. Let's see how a parallel circuit responds.

11. Remove the resistor, the LEDs, and the jumper wires from the breadboard but leave the power supply from FRED plugged in.

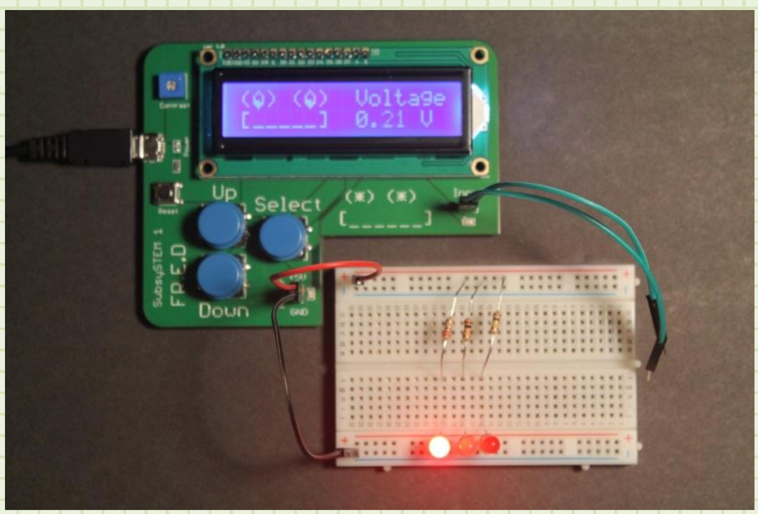
12. Select a 220 Ω resistor and plug it into the top Red power strip and the other lead into hole 20f. Take an LED and place the positive lead into hole 20j and the negative lead into the lower Blue power strip. The LED is lit because you have completed the circuit from the positive power supply through the resistor and the LED to the negative power supply. Notice how much brighter it is than when we had the three LEDs hooked in series.

13. Select another 220 Ω resistor and plug it into the top Red power strip and the other lead into hole 18f. Take an LED and place the positive lead into hole 18j and the negative lead into the lower Blue power strip. Now you have two LEDs lit. Did they get dim when you plugged in the second LED? No they didn't. Unlike the series circuit, the parallel circuit supplies the same voltage to each leg of the parallel circuit so something that happens in one branch doesn't affect the other. This is why your house is wired in parallel. When you plug in a radio, you do not want your lights to dim. Every outlet is supplied with the same voltage all the time.

14. Select another 220 Ω resistor and plug it into the top Red power strip and the other lead into hole 16f. Take an LED and place the positive lead into hole 16j and the negative lead into the lower Blue power strip. Now you have all three LEDs lit. And they are all at the same brightness. But unlike the series circuit, I don't have to have the same current going through each branch. There are identical currents right now because we have the same LEDs (red LEDs) and the same resistors in each branch. Let's change that.



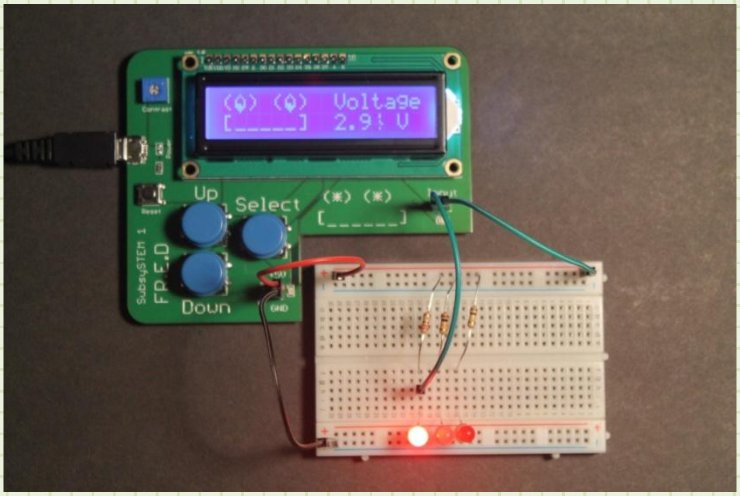
15. Remove the second resistor plugged into 18f and the power strip and replace it with a 10 kΩ resistor. Remove the third resistor and replace it with a 100 kΩ resistors. What do you see? You probably see that the first LED is at the same brightness, but the other two are now dimmer. The current in these branches is less than before because we increased the resistance in these branches. Sometimes, it is difficult to distinguish the different light levels of an LED. LEDs are amazingly efficient and will operate down to very low currents.



We want to calculate the current in these branches. Can you figure out how we could do this? The LEDs are not like resistors. They tend to have the same voltage across them when they are lit. The voltage drop across them is not proportional to the current like in resistors. Ah, but we have a resistor in each branch. Since we know the resistor values and we can measure the voltage drop with FRED, we can calculate the current through each branch of this parallel circuit using Ohm's Law.

15. Hook up the Test cable to FRED's Input port. These jumpers are now connected to the input of FRED's voltage meter. When you want to test the voltage across a component, you just connect one of the jumpers to one side and the other to the other side of the component.

16. Let's look at the current in the first branch. Hook one of the voltage meter's leads to the Red power strip and the other lead to the bottom of the first resistor (hole 20h). The meter is now connected across the resistor and FRED should be reporting the voltage.



Record the voltage below:

$$Voltage_{R1} = \_\_\_\_\_\_\_\_$$

The Ohm's Law equation for current through the resistor is:

For R1: $$I = \frac{E}{R}$$

Plugging in the Voltage you recorded above and the resistance value of 220 Ω, you can now solve for the current. (On my board, I got 3.05 V across R1 so I will use that).

For R1: $$I = \frac{E}{R} = \frac{3.05V}{220\Omega} = 0.01386A = \mathbf{13.9\ mA}$$

You should get a number close to this for your calculation. Let's repeat this for the second resistor. Move the voltage meter lead from the bottom of resistor 1 to resistor 2. This is a 10 kΩ resistor. Record the voltage:

$$Voltage_{R2} = \_\_\_\_\_\_\_\_$$

Then repeat the current calculation for this resistor (I got 3.30 V for the voltage).

For R2: $$I = \frac{E}{R} = \frac{3.30V}{10{,}000\Omega} = 0.00033A = 0.\mathbf{33\ mA}$$

See if you can take the voltage and calculate the current through the third resistor.

I got 3.35 V for the voltage across resistor 3.

$$Voltage_{R3} = \_\_\_\_\_\_\_\_$$

For R3: $$I = \frac{E}{R} = \frac{3.35V}{100{,}000\Omega} = 0.0000335A = \mathbf{0.034\ mA}$$

Now you can see why the last two LEDs are dimmer. The current through them is very small compared to the first LED.

17. Finally, remove the first LED from the board. Was there any change to the other two LEDs? No, the other 2 LEDs remained lit at their current brightness levels.

We have seen that parallel circuits differ from series in that the voltage across each parallel leg is constant and not influenced by the activity in the other legs of the circuit. But, also unlike series circuits, the current can be different in different legs of the circuit.

Conclusion

We covered some new concepts in this module. Let's look at some highlights:

1. We saw the comparison of series and parallel circuits and how each has its own characteristics of voltage and current.

2. Parallel circuits all have the same voltage across their parallel branches, but can have different currents in each branch.

3. We hook up our homes in a parallel circuit so the full supply voltage is available at every one of our outlets.

4. We saw how Ohm's Law can calculate the current through a resistor if we measure the voltage and know the resistor value.

5. We saw that LED brightness is proportional to the current through them.

6. Like the series circuit, we learned that resistors in parallel may be combined into an equivalent single resistor by using a reciprocal formula to combine them. We also learned that the combined resistance will always be smaller than the smallest resistance used.

We have discussed series and parallel circuits. But what if you have a single circuit that has both series and parallel components in it? Let's dive into this topic and show how these equivalent resistor equations and Ohm's Law will allow us to solve these complex circuits.

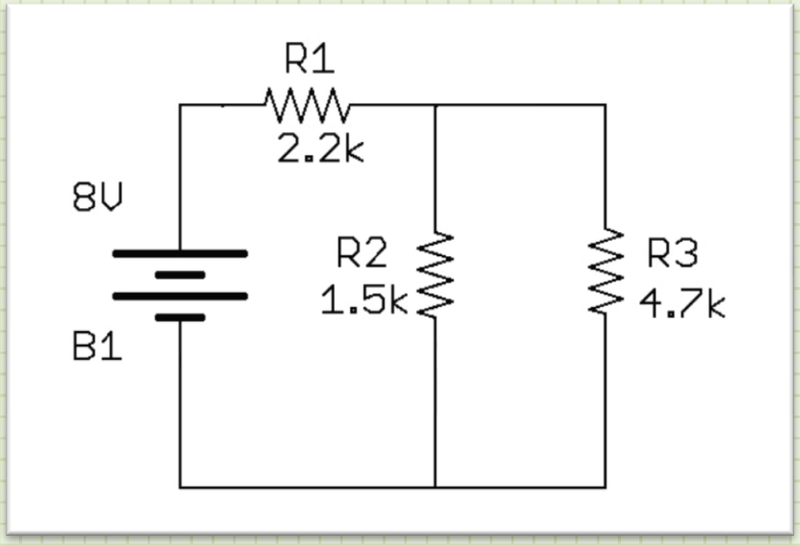
Module

4

MOD4: Combination Circuits

Up to this point, we have looked at series and parallel circuits individually. The reality is that most electronics combine series and parallel circuits together. Let's look at a simple example.

The Series/Parallel Combination Circuit



If we trace the current flow through the above circuit, we see that current leaves the positive pole of the battery (we are using conventional current), and goes through resistor R1. From there, the current splits and some goes through R2 and the rest goes through R3. The two currents then recombine to enter the negative pole of our 8 volt battery. Since the same current doesn't go through all of the components (remember that the current from R1 is getting spilt to go through R3 and R4), this circuit is not a pure series circuit. But, since R1 doesn't have the same voltage across it as R3 and R4, it is not a pure parallel circuit. We seem to have a combination of the two. So how are we going to analyze this circuit? We will use the rules we have already covered.

1. Ohm's Law: $\boldsymbol{R = \frac{E}{I}}$

2. Combining Resistors in Series: $\boldsymbol{R_{total} = R_1 + R_2 + \cdots + R_n}$

3. Combining Resistors in Parallel: $\boldsymbol{\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$

Using these three equations, we can solve even the most complex combinational circuit. Let's solve the above circuit to demonstrate the usefulness of those resistor combinational formulae.

The first step is to look at the circuit and see if there is anything we can calculate right from the start. We know the battery voltage, but we don't know the voltage across any of the resistors. We know the resistor values, but we don't know any of the currents going through them. The answer is going to be to combine resistors down until we can get to a point where we can calculate some voltages or currents. Then we can use these values to calculate other circuit values.

So, looking at our circuit, which resistors can we combine to simplify the circuit. R1 is not currently in series or parallel with any other resistor so we can't start there. R2 and R3 are in parallel so we can combine them with the parallel formula into an equivalent resistance and redraw our circuit to see if it helps us calculate any values. It is really important that we keep straight what are resistors and what are calculated equivalent resistors in our circuit so we will use subscripts to denote them clearly.

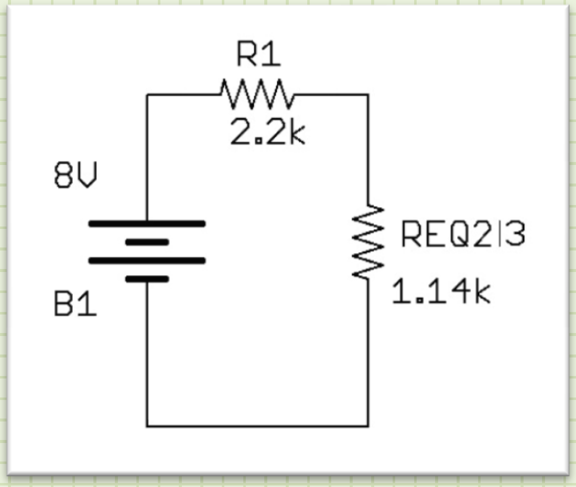
Combining R2 and R3 using the parallel resistor formula we get:

$$\frac{1}{R_{eq2|3}} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{1.5k} + \frac{1}{4.7k} = \frac{1}{1.14k}$$

Taking the reciprocal to solve for the equivalent resistance:

$$R_{eq2|3} = \mathbf{1.114k}\Omega$$

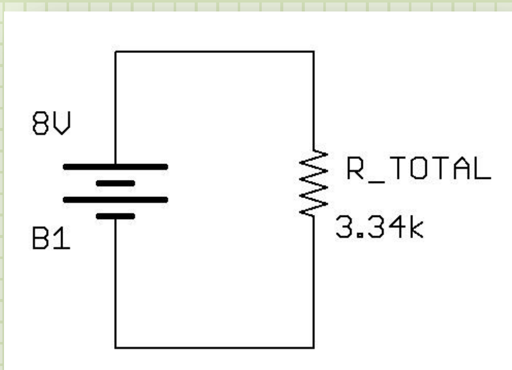
As far as the circuit is concerned, there is no difference if you use a single resistor of 1.114k or the parallel combination of R2 and R3. So let's redraw our circuit with this resistance replacing our parallel resistors.



With the parallel resistors replaced by the equivalent resistance, the circuit now looks very familiar. We have turned this combinational circuit into a simple series circuit. Now let's take a minute to see if this has allowed us to calculate anything new. We still don't know the voltage drop across either of these resistances or the current in the circuit. Let's combine our resistors with the series combination equation and look at the resulting circuit.

$$R_{total} = R_1 + R_{eq2|3} = 2.2k + 1.14k = \mathbf{3.34k}$$

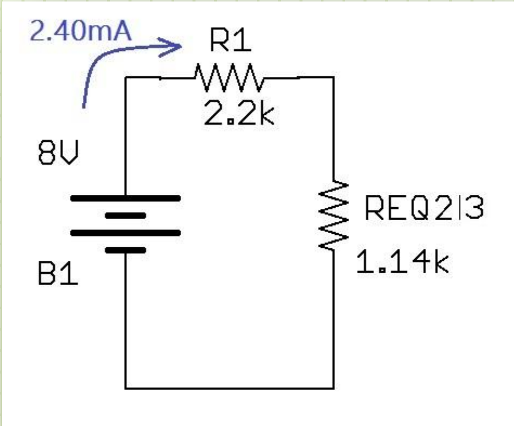
Replacing our two series resistances with this new total resistance yields the following:



I hope this gives you an idea of how powerful these rules are when analyzing complex equations. By being able to represent these resistors as equivalent resistances, we have reduced the whole circuit down to an equivalent single power supply and single circuit resistance. Now when we look at this circuit we finally have a resistor that has a known resistance and a known voltage across it. That means we can apply Ohm's Law to determine the current through this resistor. Let's apply Ohm's Law to this total resistance.

For the Circuit: $I = \frac{E}{R} = \frac{8V}{3340\Omega} = 0.002395A = \mathbf{2.40\ mA}$

So this means that the current leaving the battery and going into the whole circuit is 2.40 mA. That means we have everything defined for this circuit. Let's take this current to the next level of our equivalent circuit.



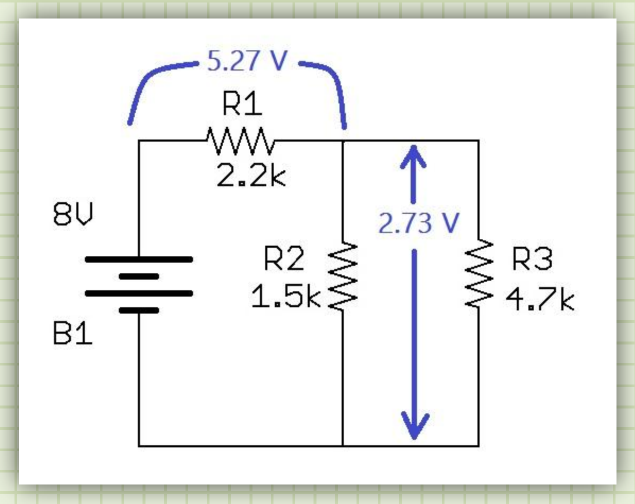
We learned in a series circuit that the current is the same through all the components. If the battery is putting out 2.40mA, then the current going through R1 and the equivalent resistance has to be that same 2.40mA. This means we know the current and the resistance of both of these so we can calculate the voltages across them. Let's use Ohm's Law to do this.

For R1: $E = I\ x\ R = 0.002395A\ x\ 2200\Omega = \mathbf{5.27\ V}$

And the voltage across the equivalent resistance:

For $R_{eq1|2}$: $E = I\ x\ R = 0.002395A\ x\ 1140\Omega = \mathbf{2.73\ V}$

A quick check of Kirchhoff's Voltage Law shows that the two resistor voltages added together equals the 8V supply. That is a good check of our math.



Why did we calculate the voltage over the equivalent resistance? After all, this isn't an actual resistor but the parallel combination of 2 resistors (R2 and R3). If you remember, voltages across parallel branches are all equal. So the voltage we calculated across the equivalent resistance is the voltage across the two parallel resistors. We can now go to our original circuit and see what is left to calculate. We know the current and voltage of R1. We know the voltage across R2 and R3, but we do not know the current through each of these resistors. Since we have these two quantities, we can use Ohm's Law to calculate the current through each branch of this parallel circuit. After, we can use Kirchhoff's Current Law to see if the sum of the two currents equal the total circuit current (it should, but we'll verify it).

For R2: $I = \frac{E}{R} = \frac{2.73V}{1500\Omega} = 0.00182A = \mathbf{1.82\ mA}$

For R3: $I = \frac{E}{R} = \frac{2.73V}{4700\Omega} = 0.000581A = \mathbf{0.58\ mA}$

And, in fact, the two currents add to 2.4 mA which is the total circuit current.

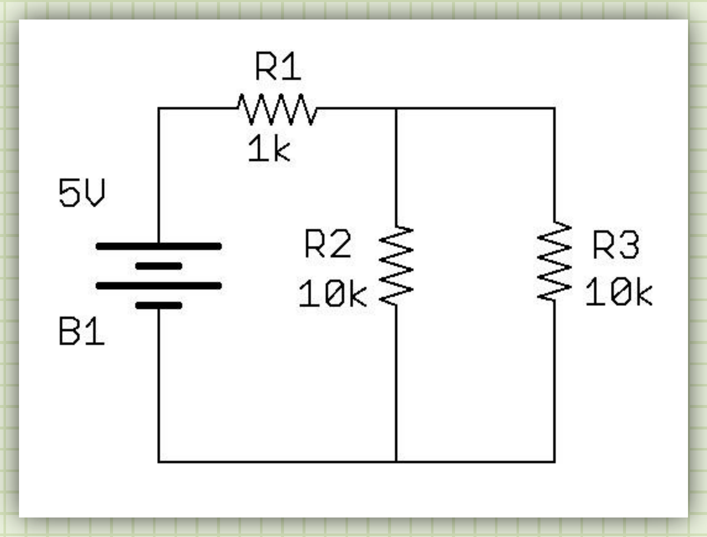
These problems can be very challenging when you first start out. There will be a desire to plug in Ohm's Law with any voltage and any resistance to get "some" current, but you have seen that you can only apply it to a given element and can't mix and match.

Let's go into the lab and do another circuit and measure our readings to confirm our calculations.

MOD 4: LAB

Series/Parallel Circuit 1

Welcome to the MOD4 Lab! In this lab we will use FRED to supply voltage to a circuit we create, do calculations predicting voltages across the components,



and use FRED to actually measure those voltages to ensure we are correct. We will use the same circuit layout that we have already looked at but will use values we can test after we build the circuit. We will use FRED's 5V supply and three resistors. We'll wire a 1k resistor in series with two 10k resistors in parallel. As before, let’s combine this circuit into simpler circuits so we can do some calculations. Let's proceed as we did in our example.

Combining R2 and R3 using the parallel resistor formula we get:

$$\frac{1}{R_{eq2|3}} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{10k} + \frac{1}{10k} = \frac{1}{5k}$$

Taking the reciprocal to solve for the equivalent resistance:

$$R_{eq2|3} = 5\ \boldsymbol{k}\Omega$$

As before, this equivalent resistance is in parallel withR1 and we can calculate the total circuit resistance.

$$R_{total} = R_1 + R_{eq2|3} = 1k + 5k = \mathbf{6}\ \boldsymbol{k}\Omega$$

Let's apply Ohm's Law to this total resistance to calculate the total circuit current.

For the Circuit: $I = \frac{E}{R} = \frac{5V}{6000\Omega} = 0.000833A = \mathbf{0.833\ mA}$

We can then calculate the voltage drops across R1 and our parallel resistor combo.

For R1: $E = I\ x\ R = 0.000833A\ x\ 1000\Omega = \mathbf{0.83\ V}$

And the voltage across the equivalent resistance:

For $R_{eq1|2}$: $E = I\ x\ R = 0.000833A\ x\ 5000\Omega = \mathbf{4.17\ V}$

Let's head into the lab to see these voltages for ourselves.

Objective:

In this lab you will create a series/parallel combination circuit and observe the voltages across the series resistor and across the parallel branch. You will compare the calculated values with the readings of the voltage to verify the circuit.

Materials:

You will need FRED, one 1 kΩ resistor, two 10 kΩ resistors, hook up wires, and the breadboard.

Procedure:

1. Power on FRED and press RST to ensure a clean boot up.

2. When FRED is ready (displays the Main Menu prompt) use the Down navigation button to get to the MOD 4 menu selection and press Select.

3. FRED will show up on the left of the screen and a volt meter will be displayed on the right.

4. Hook up FRED's power supply to the breadboard:

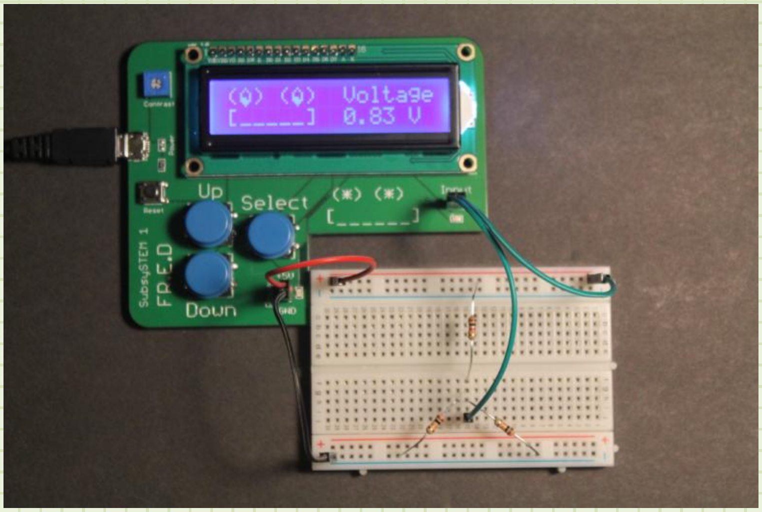
WARNING: Never directly connect the 5V and Ground connections of FRED directly together. This would cause the power supply on FRED to try to supply way too much current and could damage FRED or the device supplying power to FRED.

a) Connect the Power Cable to the power header on FRED so the red lead is connected to the 5V side and the black lead is connected to the GND side.
b) Connect the Red lead from the Power connector to the upper Red breadboard power strip and the Black lead from the Power connection on FRED to the lower Blue power strip on the breadboard.

5. Select the 1 kΩ resistor based on the color bands. Place the resistor in the breadboard putting one lead of the resistor in the upper Red power strip and the other lead in hole 15f.

6. Place one end of the 10k resistors in hole 15g and the other end in the lower Blue power strip. Place the other 10k resistor by putting one end in hole 15h and the other in the lower Blue power strip.

7. As always, trace out the circuit yourself and ensure it is in accordance with the schematic.

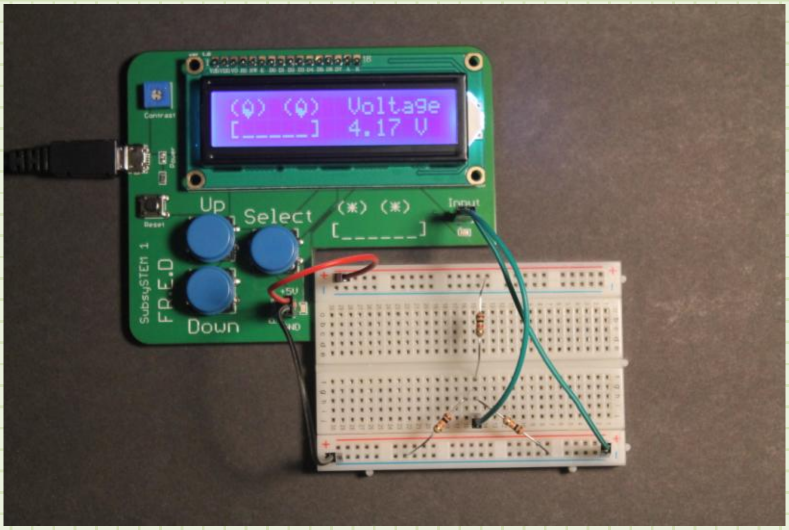


8. Hook up the Test cable to FRED's Input port. These jumpers are now connected to the input of FRED's voltage meter. When you want to test the voltage across a component, you just connect one of the jumpers to one side and the other to the other side of the component.

9. Place the volt meter jumpers into the breadboard to measure the voltage across R1. You can do this by placing one jumper into the upper Red power strip and the other into hole 15j. Record the voltage reading.

$$\boldsymbol{Voltage_{R1}} = \_\_\_\_\_\_\_$$

This value should be very close to what you calculated (0.83 V). Remember that resistors have tolerance to them and the reading may be off a little, but should be very close.



10. Measure the voltage across the parallel resistor combination of R2 and R3. You can do this by just moving the jumper from the upper Red power strip to the lower Blue power strip. Prove to yourself that we are in fact measuring across R2 and R3. Record the voltage reported by FRED.

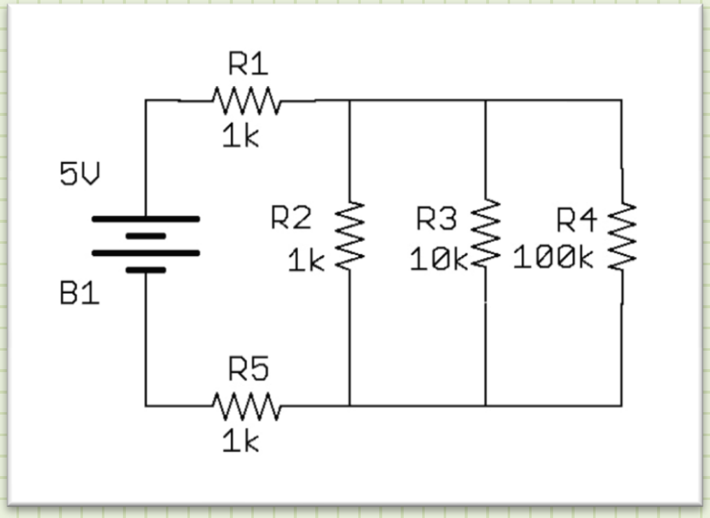
$$Voltage_{R2|R3} = \_\_\_\_\_\_\_\_$$

Notice that this is both the voltage across R2 and R3. Resistors in parallel have the same voltages across them. You should get something very close to what we calculated (4.17V).

Let's try one more circuit.

Series/Parallel Circuit 2

Let's add some complexity by adding another series and another parallel resistor. The circuit may look complicated, but we will still just use the parallel

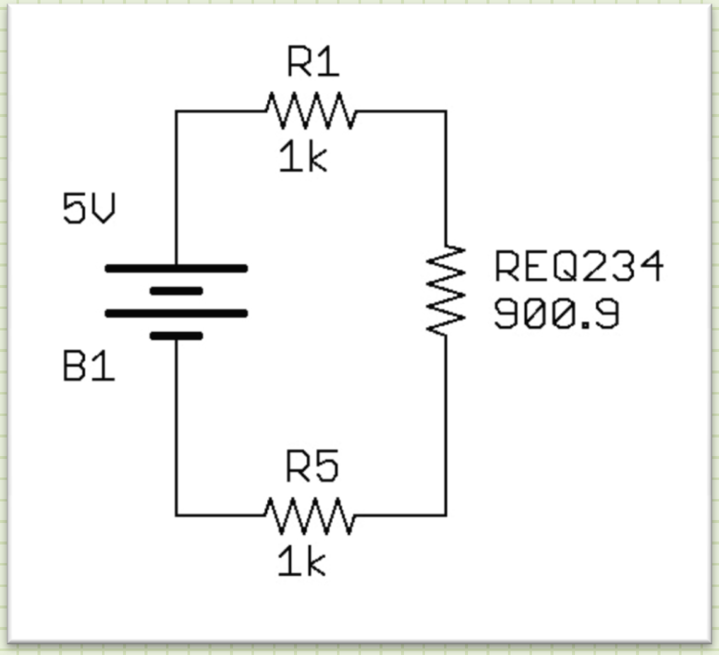


and series resistor equations to combine them into a simpler circuit. We can then use Ohm's Law to calculate voltages and currents through the circuit. Looking at the circuit, we see that current leaves the battery and goes through R1. It then goes on and splits into three different currents and flows down resistors R2, R3, and R4. The current then recombines into one current that then flows through R5 and then back to the battery. Let's start like we have in the past by simplifying this circuit by combining the resistors in parallel into an equivalent resistance using the parallel resistance formula.

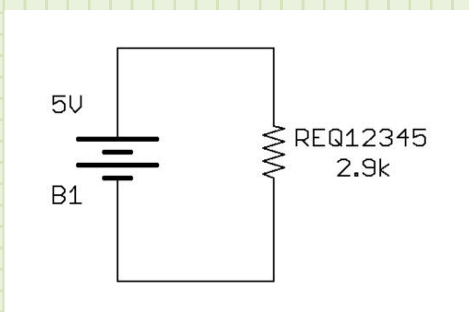
$$\frac{1}{R_{eq2|3|4}} = \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} = \frac{1}{1k} + \frac{1}{10k} + \frac{1}{100k} = \frac{1}{900.9\Omega}$$

$$R_{eq2|3|4} = \mathbf{900.9\Omega}$$

That means that the three parallel resistors can be replaced with a single 900Ω resistor. Let's look at what the circuit looks like now. With the parallel resistors replaced, the circuit is just a series circuit with R1, R5, and the equivalent parallel resistance. We still don't know the current or any of the voltage drops across the resistors yet so let's keep reducing the circuit. Let's use the series resistor formula to add the series resistances and come up with a total circuit resistance.



$R_{total} = R_1 + R_{eq2|3|4} + R_5 = 1k + 901 + 1k = \mathbf{2.9\ k}\Omega$



The application of the series and parallel resistance equations has reduced the problem to a single power source and a single resistance. We are now in a position to apply Ohm's law to calculate the total circuit current.

For the Circuit: $I = \frac{E}{R} = \frac{5V}{2.9k\Omega} = 0.001724A = \mathbf{1.72\ mA}$

This circuit current represents the current supplied by the battery to the circuit. If we refer back to our series circuit, we can now use this current to calculate the voltages across R1, R5, and the parallel combination since this current is the same current through all of these components.

For R1: $E = I\ x\ R = 0.001724A\ x\ 1000\Omega = \mathbf{1.72\ V}$

For $R_{eq2|3|4}$: $E = I\ x\ R = 0.001724A\ x\ 900.9\Omega = \mathbf{1.55\ V}$

For R5: $E = I\ x\ R = 0.001724A\ x\ 1000\Omega = \mathbf{1.72\ V}$

This gives us voltage and current for R1 and R5. To complete our analysis of the circuit, we need to calculate the currents through R2, R3, and R4. This is easily done now that we have the voltage across those resistors. Remember that the voltage across a parallel circuit is the same for all branches of that parallel circuit.

For R2: $I = \frac{E}{R} = \frac{1.55V}{1000\Omega} = 0.00155A = \mathbf{1.55\ mA}$

For R3: $I = \frac{E}{R} = \frac{1.55V}{10000\Omega} = 0.000155A = \mathbf{0.155\ mA}$

For R4: $I = \frac{E}{R} = \frac{1.55V}{100000\Omega} = 0.0000155A = \mathbf{0.0155\ mA}$

A quick check shows that these three currents added together gets us the 1.72 mA total circuit current. Let's set this circuit up and test our calculations.

Objective:

In this lab you will create a series/parallel combination circuit and observe the voltages across the series resistors and across the parallel branch. You will compare the calculated values with the readings of the voltage to verify the circuit.

Materials:

You will need FRED, three 1 kΩ resistors, one each of 10k and 100kΩ resistors, hook up wires, and the breadboard.

Procedure:

1. Power on FRED and press RST to ensure a clean boot up.

2. When FRED is ready (displays the Main Menu prompt) use the Down navigation button to get to the MOD 4 menu selection and press Select.

3. FRED will show up on the left of the screen and a volt meter will be displayed on the right.

4. Hook up FRED's power supply to the breadboard:

> ***WARNING: Never directly connect the 5V and Ground connections of FRED directly together. This would cause the power supply on FRED to try to supply way too much current and could damage FRED or the device supplying power to FRED.***

a) Connect the Power Cable to the power header on FRED so the red lead is connected to the 5V side and the black lead is connected to the GND side.
b) Connect the Red lead from the Power connector to the upper Red breadboard power strip and the Black lead from the Power connection on FRED to the lower Blue power strip on the breadboard.

5. First, we are going to construct the parallel section. We will use rows 10 and 20 to be the ends of the parallel branch. Grab a 1k resistor and place one end into hole 10b and the other end into 20b. Take the 10k resistor and place it in 10c and 20c. Place the 100k resistor in 10d and 20d. That completes the parallel portion of the circuit.

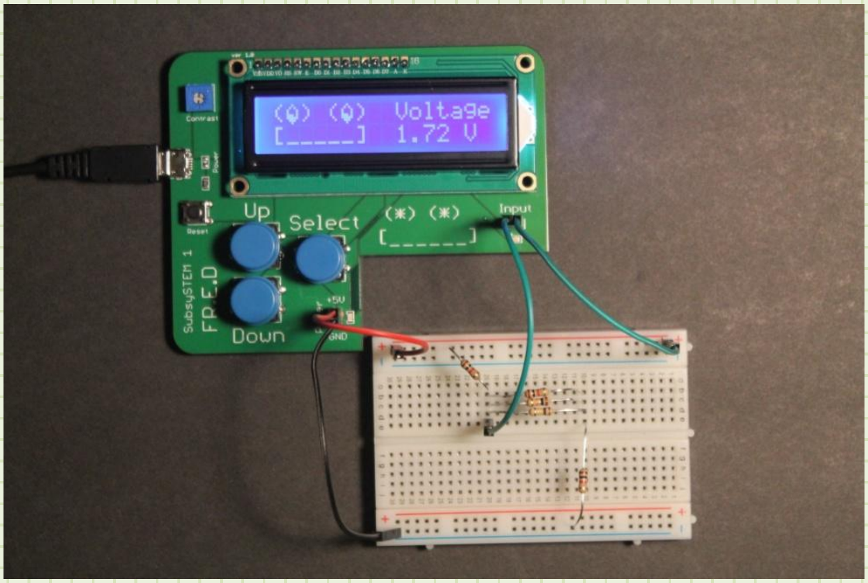
6. Let's hook up R1. Take a 1k resistor and place it in the upper Red power strip and hole 20a. Now we will hook up R5. Place the other 1k resistor in hole 10e and the other end in the lower Blue power strip. This completes the circuit setup. Convince yourself it matches our schematic.

7. Hook up the Test cable to FRED's Input port. These jumpers are now connected to the input of FRED's voltage meter. When you want to test the voltage across a component, you just connect one of the jumpers to one side and the other to the other side of the component.

Referring to our circuit, let's take the voltages available to us.

8. Read the voltage across R1. Attach one of the input jumpers to the upper Red power strip and the other jumper to hole 20e. Record the voltage.

$$\boldsymbol{Voltage_{R1}} = \_\_\_\_\_\_\_\_$$



We calculated 1.72V. You should get a voltage very close. Hopefully you can see by now that analyzing a circuit is not just a math exercise but a way to truly determine the voltages present in a real circuit. More importantly, it gives us the ability to design circuits given desired voltages and currents. You have started to dabble in the world of the electronics designer and electrical engineer. Let's measure the voltage across the parallel resistors.

9. Move the input jumper in the upper Red power strip to hole 10a. Verify this is the voltage across our parallel resistors R2, R3, and R4. Record the voltage.

$$\boldsymbol{Voltage_{R2|3|4}} = \_\_\_\_\_\_\_\_$$

Our calculation showed it should be 1.55V. Does it match your reading?

10. Let's finish by measuring the voltage across R5. Move the input jumper in 20e to the lower Blue power strip. Record the voltage.

$$\boldsymbol{Voltage_{R5}} = \_\_\_\_\_\_\_$$

This should be 1.72V (or pretty close at least).

Feel free to repeat this lab with different resistor combinations. There is no substitute for doing a lot of problems to get comfortable with these circuit analysis methods. Remember, do not do anything that would connect the positive and negative power supply connections directly together or apply more than 5V to the inputs.

Conclusion

Series/Parallel circuits can look very complex. But we have seen that by using the series and parallel combination equations to combine resistors into equivalent resistances we can reduce the complexity of a circuit. In our examples, after combining the parallel resistors into an equivalent resistance and redrawing the circuit, we were left with a simple series circuit. Practice will increase your skill in quickly analyzing these types of circuits.

Here are some of the takeaways from this module.

1. Complex series/parallel circuits can be analyzed by reducing them to simpler circuits using the series and parallel resistor combination equations.

2. When you calculate the voltage across a parallel resistor combination, that voltage is the same voltage across each parallel resistor.

3. Rewriting circuits with the combination resistances can help greatly in visualizing how to proceed in the analysis of that circuit.

4. Ohm's Law can only be applied across discrete (individual) items. It is easy to want to take the circuit voltage and divide it by an individual resistor to find

that resistor's current. But if you apply Ohm's Law to a resistor, you need to use the voltage across that resistor to find the current through that resistor. Using subscripts in Ohm's Law calculations will help keep this requirement clear.

Well done! You now have the tools to reduce electronic circuits to simpler circuits and you can calculate the circuit parameters from these new circuits with Ohm's Law. Speaking of tools, the next module will discuss some of the tools available to technicians to analyze electronic circuits and signals.

Module

5

MOD5: Test Equipment

Calculating electronic values of current, voltage, and resistance is only part of the skill set of the electronics technician. To be able to troubleshoot real equipment, you have to be able to actually measure values in the circuit. Looking for problems in power supplies and the loss of signals through equipment are basic strategies of some troubleshooting. So let's look at some of these test devices.

The Voltmeter

You are actually familiar with the first device. A **voltmeter** is a device that allows you to measure the voltage across some part of a circuit. You have been using FRED's voltmeter in your labs. When you hooked the test leads across a resistor, FRED calculated the difference of potential between those two points and reported the result as a voltage. There are two basic types of voltmeters; analog and digital.

Analog meters use a mechanical meter to display voltage. Digital meters use a digital display to indicate voltage. Each type has its advantage and disadvantages. It is becoming increasingly rare to find analog meters in use by technicians, but there are still some times that their advantages outweigh their drawbacks.

Here is a typical analog multimeter. This is considered a multimeter because it does more than just read voltage. You can distinguish an analog meter by the fact that it has a mechanical meter movement.

One of the luxuries you were provided by using FRED as your voltmeter is that he can distinguish positive and negative voltages. You were not required to hook up the probe leads a certain way. In an analog meter, that is not the case. If we send that current the wrong way (reverse polarity) it would try to drive the needle the wrong way and potentially damage the meter.

Or you can just use a digital auto-ranging multimeter, set it for DC voltage, attach the leads to the circuit under test and directly read the voltage on the display. It sounds much easier. And it is. But there are a few reasons why analog meters have an advantage.

1. They do not require power to measure voltage or current in a circuit. Because the power for deflecting the needle comes from the circuit under test, there is no need for an external power source.

2. They have the ability to show changing dynamics in a circuit better than most digital voltmeters. Sometimes you want to see a voltage rise and drop as it happens like when you are testing sensors or looking at low frequency signals. The needle instantly tracks changes in the input. A digital meter needs to figure out what the voltage is (we'll cover this in a bit) and this takes some time. Also, since a digital meter just shows a number, for some signals, we would just observe numbers flashing on the meter every half second and it would be very difficult to determine a trend from this information.

The Digital Voltmeter

The meter shown here is a digital meter as can be seen from the digital (non-mechanical) display. Digital meters have the advantage of being very easy to read the measured voltage. There is no chance of reading the voltage off of the wrong scale because there is no scale. You just read the value of voltage directly off the display. Because digital meters are driven by computers, they have the ability to do more than just read voltages. Advanced meters may be able to store and transfer voltage readings to a computer, calculate signal frequencies, read complex digital signals and more.

FRED includes a voltmeter for you to use. If you boot up FRED and menu down beyond MOD 4, you will see the selection "VOLT meter." Click select and you will be brought to the voltmeter section. Unlike in the lab, this voltmeter gives you a little better precision. FRED can actually resolve voltage down to about 0.005V (or 5mV). This readout gives you three decimal places so you get a little better resolution with this voltmeter. Remember to never apply more than 5V to this voltmeter.

Mini LAB

Let's do a quick mini lab to use our voltmeter and get a look at a light sensitive resistor. You should be very familiar with the lab equipment now so I will just describe the lab and allow you to hook it up the way you would like.

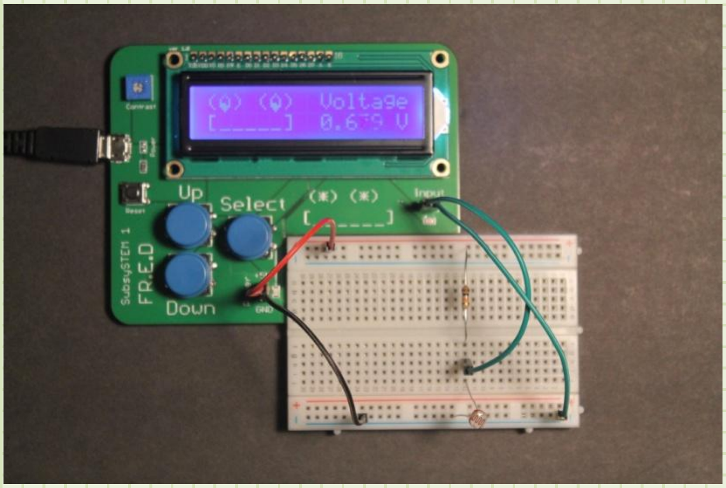
1. Turn on FRED, menu down and select the VOLT Meter menu item.

2. Hook up FRED's power to the breadboard as usual (5V to the upper Red and GND to the lower Blue power strips).

3. Hook up a 10k resistor in series with a photoresistor between the Red and Blue power strips.

4. Hook FRED's voltmeter inputs on either side of the photoresistor to measure its voltage.

5. While observing the voltage, alternately cover and uncover the photoresistor with your hand. What happens?



The photoresistor is a device that varies its resistance based on the amount of light falling on its surface. As the resistance varies, the current through the circuit changes which changes the voltage dropped by the 10k resistor. This varies the voltage felt across the photoresistor. Photoresistors are often used in automatic nightlights to turn on the light when the ambient light is low and to shut it off when there is a lot of ambient light.

Let's continue our discussion of test equipment.

The Ammeter

Our voltmeter was a device to measure voltage. The **ammeter** is a device we use to measure current. An analog ammeter uses the same principle as the voltmeter discussed previously. If you remember, the voltmeter actually caused needle movement by creating a current through the coil which created the magnetic field that deflected the meter. Since this system uses current to create a deflection, we can use it to measure current directly in our circuit.

One of the major differences in testing current through a component from testing the voltage across the component is that our ammeter actually needs to be in the current stream to be able to measure it. With the voltmeter, we could just probe either side of the component and measure the voltage. With current, we need to be in the circuit so this makes current measurements a little harder to obtain than voltage.

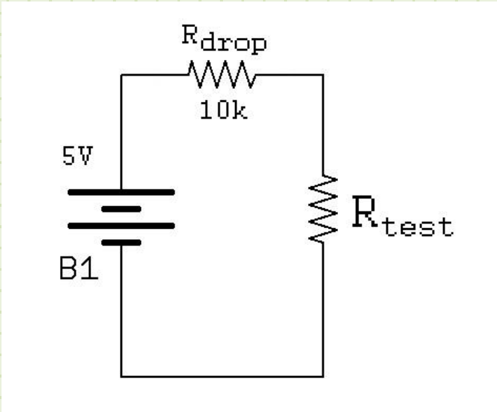
The Ohmmeter

A device that measures resistance is called an **ohmmeter**. It is usually included in a multimeter, but standalone ohmmeters exist. There are ways to calculate the resistance of many things, but the most direct way to measure resistance is by applying a voltage, measuring the current, and using Ohm's Law to calculate the resistance. This is what is happening in the ohmmeter. An internal voltage is applied to the resistor under test. The resultant current is measured, and a scale for the meter is chosen to display the resistance associated with that voltage and current.

One of the precautions associated with using an ohmmeter is that you must ensure you de-energize the circuit under test. If you applied the test leads to a circuit under power, you may apply too large a voltage to the ammeter section of the ohmmeter and may destroy it. Always ensure that you have removed power from the circuit before you take resistance readings to protect your test equipment.

We can use this concept to create an ohmmeter with FRED. Since FRED is able to measure voltages, let's look at how we can use that to create a voltage sensing ohmmeter.

Mini LAB



Let's do another quick mini lab to measure resistors using FRED's voltmeter. First, let's establish how we can do this.

Look at this circuit. What is the unknown in this circuit? It is the resistor under test (R_{test}). If we knew this value, we could analyze the whole circuit for all electronic values. However, if we could measure the voltage across R_{test} , we could then calculate the resistance. Let's see how to do this. First, let's calculate the total current in the circuit. I know, we can without knowing R_{test}, but let's carry that value through and see if we can ever relate it to the voltage across this resistor so FRED can relate the voltage (which he can calculate) to the resistors resistance (which he can't directly measure).

For the circuit: $I = \frac{E}{R} = \frac{5V}{R_{drop}+R_{test}} = \frac{5V}{10k+R_{test}}$

We also know that the circuit current is the same through each of these resistor because of the characteristics of the series circuit. We can then draft up an Ohm's Law equation for voltage across the test resistance with respect to the voltage across it.

For the test Resistor: $E = I \ x \ R = I_{circuit} \ x \ R$

Now we have two equations that relate the values we need. Let's plug the first into the second and solve for R_{test}.

$$E_{R_{test}} = \frac{5V}{10k + R_{test}} \ x \ R_{R_{test}}$$

$$\boldsymbol{R_{test} = \frac{10k\Omega \ E_{R_{test}}}{5V - \ E_{R_{test}}}}$$

Ohm's Law and some fancy math got us to solve for an equation that relates the voltage across the test resistance to the resistance itself. Pretty cool. We programmed FRED with this formula so let's see it in action.

1. Turn on FRED, menu down and select the OHM Meter menu item.

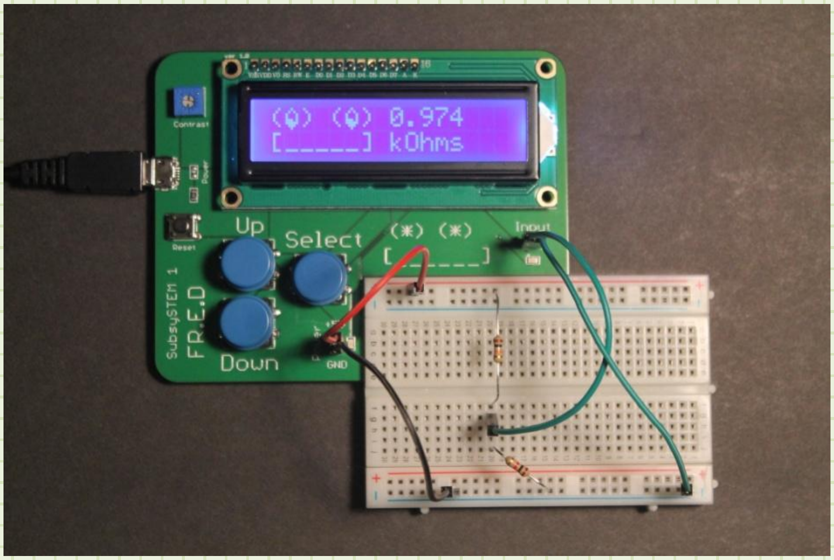
2. Hook up FRED's power to the breadboard as usual (5V to the upper Red and GND to the lower Blue power strips).

3. Hook up a 10k resistor from the Red power strip to hole 20f.

4. Hook a test lead from FRED's input to hole 20g and the lower Blue power strip.

5. FRED is now ready to measure resistors. Take a resistor from your kit and hook it between hole 20j and the lower Blue power header. FRED is now set to read the voltage across that resistor and, using the above derived formula, calculate and display the resistance.

You may see the resistance value jump around a bit, but it will be easy to distinguish the 1k, 10k, and 100k resistors. This is a helpful thing to do if you are having trouble reading the resistor bands. You can come back to this mini lab and use it to separate out your resistors again by value.



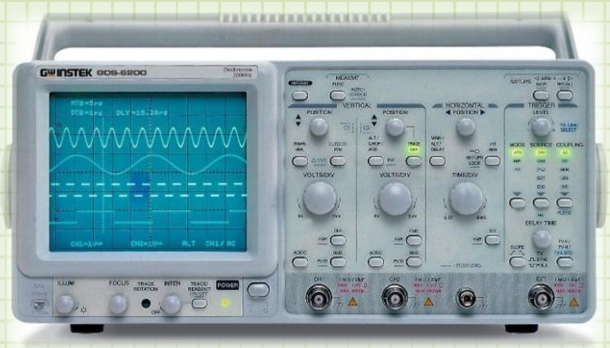
Above, FRED is testing a 1k resistor and reporting 974 Ω. When measured with a commercial ohmmeter, the same resistor read 980 Ω. Not too shabby FRED.

You will notice that FRED displays a value when no resistor is being tested. That is just a result of the math and the maximum value FRED can handle. Disregard any reading when no resistor is under test.

You can also connect multiple resistors in parallel and series to see the effect of adding resistors. Experiment with different combinations.

Oscilloscope

An oscilloscope is an electronic test device that allows electronic technicians to see signals that are present in electronic equipment. Often in complex amplifiers, radios, and video equipment, it is important to see what is actually



happening as a signal passes through certain stages. An oscilloscope can display the values of the voltage of a waveform over time so you can get a visual of the signal. You can see signal type, measure key parameters like peak voltage and frequency, and even see noise and interference.

Function Generator

A Function Generator is an electronic test device that allows the user to create

a specific signal for use in troubleshooting, testing, and aligning electronic equipment. Let's assume a technician wants to troubleshoot a radio transmitter that isn't working. She may decide to use a function generator to inject an audio signal into the input of the transmitter. The she could use an oscilloscope to look at that signal as it is passed to the various stages of the transmitter as it conditions and modifies it for transmitting. When she gets to a stage where the input signal looks good, but the output signal is bad, she knows she is in the right spot. Now she takes out her multimeter to take voltage, current, and resistance readings on that stage to determine the faulty component. This is a typical troubleshooting process and it used all of this test equipment.

Conclusion

Test equipment can help technicians understand circuits and troubleshoot them when they fail. Here are some of the key takeaways from this module.

1. A multimeter is a tool that usually comprises a voltmeter, ohmmeter, and ammeter. It often contains other functions too, but these are primary.

2. A circuit must be de-energized to take resistance reading with an ohmmeter. If voltage is present in the circuit, it could damage your meter.

3. Analog meters can be harder to read, but they require no external power to measure voltage and current and can show slow changes in circuit parameters better than a digital meter.

4. A voltmeter can take its voltage reading across a component but an ammeter must be in the current stream that it is testing.

5. An oscilloscope is used to get a visual image of a waveform in a piece of electronic gear. It shows many characteristics of a signal you just cannot get from a multimeter.

6. A function generator is used to create a desired signal so a technician can create a known input to devices to check for proper output.

There are many other test instruments that electronic technicians use, but this module was intended to introduce the most basic instruments needed to assess most circuit conditions.

Congratulations on completing this Subsystem on Basic Electronics. We hope you are encouraged in your new knowledge to continue your study of electronics.

End of Course Quiz

The following is a 25 question quiz to check your comprehension and retention of some key concepts.

1. A ____________ circuit is characterized by having the same current flowing through all of the components.
    a. Parallel
    b. Combination
    c. Series
    d. None of the above

2. A material is considered a good conductor if it has _________.
    a. low resistance to current flow
    b. an even number of protons
    c. high resistance to current flow
    d. an equal number of neutrons and protons

3. In an open circuit ___________.
    a. current is maximum
    b. all voltages are equal
    c. the sum of the resistances is zero
    d. there is no current flow

4. 0.235 A is how many mA?
    a. 23.5
    b. 2.35
    c. 235
    d. 2350

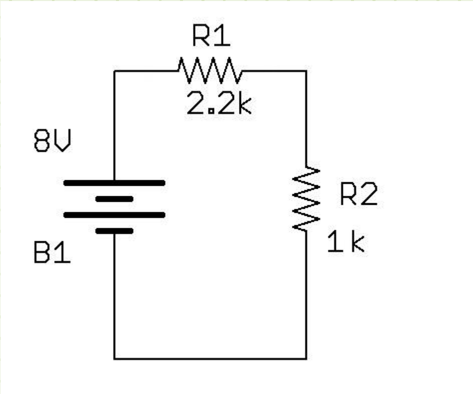
5. Knowing that 1 kg = 2.2 lbs, how many kg are there in 8.4 lbs?
    a. 3.82
    b. 18.5
    c. 6.2
    d. 10.6

6. Ohm's Law states ______.
    a. $E = {}^{I}/_{R}$
    b. $E = IR$
    c. $R = IE$
    d. $I = ER$

7. A resistor that has three bands with colors Brown/Black/Orange is what resistance value?
    a. 100 Ω
    b. 1 kΩ
    c. 10 kΩ
    d. 100 kΩ

8. What is the total resistance for three 2.2k resistors in series?
    a. 2.2 kΩ
    b. 4.4 kΩ
    c. 6.6 kΩ
    d. 733 Ω

9. What is the current through R1 in the following circuit?



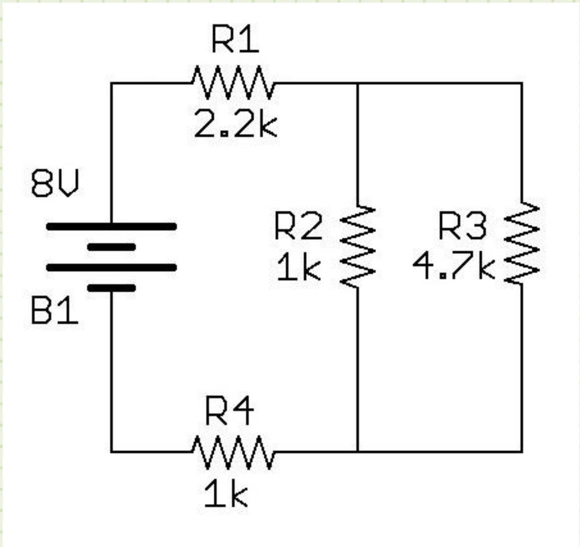
10. What is the voltage drop across R2 in the above circuit?

11. One of the advantages in analyzing a parallel circuit is ______.
    a. the current through each leg is equal
    b. the voltage across each leg is equal
    c. the total resistance is the sum of the individual resistances
    d. the total current is constant regardless of the voltage supplied

12. Kirchhoff's Voltage Law states that the sum of the voltage drops around a closed loop equals ___.
    a. the maximum voltage in that loop
    b. the minimum voltage in that loop
    c. the current times the resistance in a loop
    d. zero

13. What is the equivalent resistance of a 10k and a 4.7k resistor in parallel?
    a. 14.7k
    b. 3.2k
    c. 5.3k
    d. 4.2k

For the following circuit, answer questions 14-20.



14. What is the total circuit resistance?
15. What is the current through R1 in the circuit?
16. What is the voltage drop across R2?

17. What is the current through R2?
18. What is the voltage drop across R4?

19. What is the current through R3?

20. If R3 were to fail open, what would happen to the total current flow in the circuit?

21. One of the advantages of an analog voltmeter is______.
    a. it does not require power to operate
    b. it can measure higher voltages than digital
    c. it is easier to read than digital
    d. it is not sensitive to the polarity of the voltage input

22. For a voltmeter, it is desired for it to have________.
    a. very low internal resistance
    b. very high internal resistance
    c. the ability to pass a lot of current
    d. very high circuit loading

23. A device that changes resistance in response to a change in light level is a _______.
    a. thermistor
    b. diode
    c. semiconductor
    d. photoresistor

24. When measuring current in a circuit ______.
    a. measure across the component you want to measure
    b. measure the top of the component with respect to ground
    c. place the ammeter in the current stream you want to measure
    d. measure the same way you would measure voltage

25. When measuring resistance, ensure the component under test ____.
    a. is powered by its normal supply
    b. is powered by an external supply
    c. is not powered
    d. is only powered by a source less than the rating of the ohmmeter

Quiz Answers

1. c
2. a
3. d
4. c
5. a
6. b
7. c
8. c
9. 2.5 mA
10. 2.5 V
11. b
12. d
13. b
14. 4.02 kΩ
15. 1.99 mA
16. 1.64 V
17. 1.64 mA
18. 1.99 V
19. 0.349 mA
20. Total current would decrease

21. a

22. b

23. d

24. c

25. c