Electronics for Everybody

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Electronics for Everybody

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Contents

Chapter 1

Introduction

Welcome to the world of electronics! In the modern world, electronic devices are everywhere, but fewer and fewer people seem to understand how they work or how to put them together. At the same time, it has never been easier to do so as an individual. The availability of training tools, parts, instructions, videos, and tutorials available for the home experimenter has grown enormously, and the costs for equipment has dropped to almost nothing.

However, what has been lacking is a good guide to bring students from *wanting* to know how electronic circuits work to actually understanding them and being able to develop their own. For the hobbyist, there are many guides that show you how to do individual projects, but they often fail to provide enough information for their readers to be able to build projects of their own. There is plenty of information on the physics of electricity in physics books, but they fail to make the information practical. There are also books like *The Art of Electronics* which are great describing how to put together circuits—but only if you are studying to be an electrical engineer, and also only if you can shell out large amounts of cash.

What has been needed for a long time is a book that takes you from knowing nothing about electronics to being able to build real circuits that you design yourself. This book combines theory, practice, projects, and design patterns in order to enable you to build your own circuits from scratch. Additionally, this book is designed entirely around safe, low-current DC power. We stay far away from the wall outlet in this book to be sure that you have a safe and fun experience with electronics.

Note that this book is primarily written as a textbook for electronics classes for high-school and college students. It has problems to be worked, activities to do, and reviews at the end of each chapter. However, it can also be used as a guide for hobbyists (or wannabe hobbyists) to learn on their own. If you plan on using this book to learn on your own, we suggest that not only do you read the main parts of the chapter, but that you also do the activities and homework as well. The goal of the homework is to train your mind to think like a circuit designer. If you work through the example problems, it will make analyzing and designing circuits simply a matter of habit.

1.1 Working the Examples

In this book, all examples should be worked out using decimals, not fractions. This is an engineering course, not a math course, so feel free to use a calculator. However, you will often wind up with very long strings of decimals on some of the answers. Feel free to round your answers to a single decimal point. So, for instance, if I divide 5 by 3 on my calculator, it tells me 1.66666667. However, I can just give the final answer as 1.7. This only applies to the final answer. You need to maintain your decimals while you do your computations.

Also, if your answer is a decimal number that *begins* with zeroes, then you should round your answer to include the first 2–3 nonzero digits. So, if I have an answer of 0.0000033333333, I can round that to 0.0000033.

If you have taken physics or chemistry, and you are familiar with significant digits, you can just round your answers to 3–4 significant digits.

1.2 Tools You Will Need

FIXME—**Need to write this - breadboard, jumper wire, resistor, etc.** FIXME—**Need an "anatomy of a component" showing a resistor and the leads, as well as an LED and the positive and negative** FIXME—**Need definitions of anode and cathode** FIXME—**Need a forum URL for people with issues**

Chapter 2

Before We Begin

I put this chapter at the beginning because it is important and I wanted it easy to find, but you may not know enough to understand all of it. You can skip over this section and come back to it when you start to do projects in chapter FIXME.

2.1 General Safety Note

This book deals almost entirely with DC current from small battery sources. This current is inherently fairly safe, as small batteries are not capable of delivering the amount of current needed to injure or harm. For these projects, you can freely touch wires and work with active circuits without any protection, because the current is incapable of harming you.

However, please note that if you ever deal with AC current or large batteries (such as a car battery), you must exercise many more precautions than described in this book, because those devices can and will harm or kill you if mishandled.

2.2 Safety Guidelines

Using small-battery DC current is very safe. Nonetheless, you should employ these safety guidelines, both for your safety and for the safety of your circuit. The biggest potential problem is with the battery itself, not the electricity. Batteries are made from potentially toxic chemicals.

Please follow these guidelines, as they will both keep you safe as well as help prevent you from accidentally damaging your own equipment.

1. If you have any cuts or other open areas on your skin, please cover them. Your skin is where most of

your electric protection exists in your body.

2. Before applying power to your circuit, check to be sure you have not accidentally wired in a short circuit between your positive and negative poles of your battery.
3. If your circuit does not behave like you expect it to when you plug in the battery, unplug it immediately and check for problems.
4. If your battery or any component becomes warm, disconnect power immediately.
5. If you smell any burning or smoky smells, disconnect power immediately.
6. Dispose of all batteries in accordance with local regulations.
7. For rechargeable batteries, follow the instructions on the battery for proper charging procedures.

If you follow these common sense rules you should have a fun and safe experience!

2.3 Electrostatic Discharge

If you have ever touched a doorknob and received a small shock, you have experienced electrostatic discharge (ESD). ESD is not dangerous to you, but it can be dangerous to your equipment. Even shocks that you can't feel may damage your equipment. With modern components, ESD is rarely a problem, but nonetheless it is important to know how to avoid it. You can skip these precautions if you wish, just know that occasionally you might wind up shorting out a chip or transistor because you weren't careful. ESD is also more problematic if you have carpet floors, as those tend to build up static electricity.

Here are some simple rules you can follow to prevent ESD problems:

1. When storing IC components, store them with the leads enmeshed in conductive foam. This will prevent any voltage differentials from building up in storage.
2. Wear natural 100% cotton fabrics.
3. Use a specialized ESD floor mat and/or wrist strap to keep you and your workspace at ground potential.
4. If you don't use an ESD strap or mat, touch a large metal object before starting work. Do so again any time after moving around.

2.4 Using Your Multimeter Correctly

In order to keep your multimeter functioning, it is important to take some basic precautions. Multimeters, especially cheap ones, can be easily broken through mishandling. Use the following steps to keep you from damaging your multimeter, or damaging your circuit with your multimeter:

1. Do not try to measure resistance on an active circuit. Take the resistor all the way out of the circuit before trying to measure it.

2. Choose the appropriate setting on your multimeter before you hook it up.

3. Always err on the side of choosing high values first, especially for current and voltage. Use the high value settings for current and voltage give your multimeter the maximum protection. If they are too large, it is easy enough to turn them lower. If you had it set too low, you may have to buy a new multimeter!

Part I

Basic Concepts

Chapter 3

What is Electricity?

The first thing to tackle in the road to understanding electronics is to wrap our minds around what electricity is and how it works. The way that electricity works is very peculiar and unintuitive. We are used to dealing with the world in terms of physical objects—desks, chairs, baseballs, etc. Even if we never took a class in physics, we know the basic properties of such objects from everyday experience. If I drop a rock on my foot, it will hurt. If I drop a heavier rock, it will hurt more. If I remove an important wall from a house, it will fall down.

However, for electricity, the only real experience we have is that we have been told to stay away from it. Sure, we have experience with computers and phones and all sorts of devices, but they give us the result of processing electricity a million times over. But how does electricity itself work?

3.1 Charge

To answer this question, we need to answer another question first: what *is* electricity? Electricity is the flow of **charge**. So what is charge?

Charge is a fundamental quantity in physics—it is not a combination (that we know of) of any other quantity. A particle can be charged in one of three ways—it can be positively charged (represented by a + sign), negatively charged (represented by a - sign), or be neutrally charged (i.e., have no charge). Figure 3.1 shows what an atom looks like. In the center of the atom are larger, heavier particles called **protons** and **neutrons**. Protons are positively charged particles, and neutrons are neutrally charged particles. Together these form the **nucleus** of the atom, and determine *which* atom we are talking about. If you look on a periodic table, the big number of the element refers to how many protons it has in its nucleus, and the smaller number is usually the total number of protons and neutrons (this smaller number is sometimes a decimal because the number of neutrons can change, so it is an average).

Circling around the nucleus are **electrons**. Electrons are negatively charged particles. Even though electrons

Figure 3.1: Charged Particles in an Atom

FIXME - need drawing

are much smaller and lighter than protons, the amount of negative charge of one electron is equal to the amount of positive charge of one proton. Positive and negative charges attract each other, which is what keeps electrons contained within the atom. Electrons are arranged in shells surrounding the nucleus. The outermost shell, however, is the most important one when thinking about how atoms work.

When we think about individual atoms, we think about them when they are isolated and alone. In these situations, the number of electrons and protons are equal, making the atom as a whole electrically neutral. However, especially when atoms interact with other atoms, the configuration of their electrons can change. If the atoms gain electrons, then they are negatively charged. If the atoms lose electrons, then they are positively charged. Free electrons are all negatively charged.

If there are both positively and negatively charged particles moving around, their opposite charges attract one another. If there is a great imbalance of positive and negative charges, usually you will have a *movement* of some of the charged particles towards the particles of the opposite charge. This is a *flow* of charge, and is what is referred to when we speak of electricity.

The movement of charge can be either positively-charged particles moving towards negatively-charged ones, or the reverse. Usually, in electronics, it is the electrons which are moving through a wire, but this is not the only way which charge can move.

Electricity can be generated by a variety of means. The way that electricity is generated in a battery is that a chemical reaction takes place, but the reactants (the substances that react together) are separated from each other by some sort of medium. The positive charges for the reaction move easiest through the medium, but the negative charges for the reaction move easiest through the wire. Therefore, when the wire is connected, electricity moves through the wire to help the chemical reaction complete on the other side of the battery.

This flow of electric charge through the wire is what we normally think of as electricity.

— Making Your Own Battery

You can make a simple battery of your own out of three materials: thick copper wire or tubing, a galvanized nail (it *must* be galvanized), and a potato or a lemon. This battery operates from a reaction between the copper on the wire and the zinc on the outside of the galvanized nail. The electrons will flow from the zinc to the copper through the wire, while the positive charge will flow within the potato.

To build the battery, you must insert the thick copper and the nail into the potato. They should be near each other, but *not touching*. This is a battery that will produce about 1.2 volts of electricity. This is not quite enough to light up an LED, but it should register on a multimeter. See chapter FIXME for how to measure voltage with a multimeter.

Different plants will yield different voltages. You might experiment on this with lemons, strawberries, and other produce items to see what voltages each one produces.

Remember, however, that the potato is not actually supplying the current. What the potato is doing is creating a barrier so that only the positive charges can flow freely in the potato, and the negative charges have to use the wire. Note that this can be made even more efficient by boiling the potato first.

3.2 Measuring Charge and Current

Atoms are very, very tiny. Only in the last few years have scientists even developed microscopes that can see atoms directly. Electrons are even tinier. Additionally, it takes a *lot* of electrons moving to have a worthwhile flow of charge. Individual electrons do not do much on their own—it is only when there are a very large number of them moving that they can power our electronics projects.

Therefore, scientists and engineers usually measure charge on a much larger scale. The **coulomb** is the standard measure of electric charge. One coulomb is equivalent to about $6,242,000,000,000,000,000$ protons. If you have that many electrons, you would have -1 coulomb. That's a lot of electrons and protons, and it takes that many to do very much electrical work. Thankfully, protons and electrons are very, very small. A typical 9-volt battery can provide about $2,000$ coulombs of charge, which is over $10,000,000,000,000,000,000,000$ electrons (ten thousand billion billion electrons).

However, electricity and electronics are not about electric charge sitting around doing nothing. Electricity deals with the *flow* of charge. Therefore, when dealing with electricity, we rarely deal with coulombs. Instead, we talk about how fast the electrical charge is flowing. For that, we use **amperes**, often called amps, and abbreviated as A. 1 ampere is equal to the movement of 1 coulomb of charge out of the battery each second.

For the type of electronics we will be doing, an ampere is actually a lot of current. In fact, a full ampere of current can do a lot of physical harm to you, but we don't usually deal with full amperes when creating electronic devices. Power-hungry devices like lamps, washers, dryers, printers, stereos, and battery-chargers need a lot of current—that's why we plug them into the wall. Small electronic devices don't usually need so much current. Therefore, for electronic devices, we usually measure current in **milliamperes**, usually called just milliamps, and abbreviated as mA. The prefix *milli-* means one thousandth of (i.e., $\frac{1}{1000}$ or 0.001). Therefore, a milliamp is one thousandth of an amp. If someone says that there is 20 milliamps of current, that means that there is 0.020 amps of current. This is important, because the equations that we use for electricity are based on amps, but we are going to be mainly concerned with milliamps.

So, to go from amps to milliamps, multiply the value by $1,000$. To go from milliamps to amps, divide the value by $1,000$ (or multiply by 0.001) and give the answer in decimal (electronics always uses decimals instead of fractions).

Example 3.1 If I were to have 2.3 amps of electricity, how many milliamps is that? To go from amps to milliamps, we multiply by $1,000$. $2.3 * 1,000 = 2,300$. Therefore, 2.3 amps is the same as $2,300$ milliamps.

Example 3.2 If I were to have 5.7 milliamps of electricity, how many amps is that? To go from milliamps to amps, we divide by $1,000$. $5.7/1,000 = 0.0057$ Therefore, 5.7 milliamps is the same as 0.0057 amps.

Example 3.3 Now, let's try something harder—if I say that I am using 37 milliamps of current, how many coulombs of charge has moved after 1 minute? Well, first, let's convert from milliamps to amps. To convert from milliamps to amps, we divide by $1,000$. $37/1000 = 0.037$ Therefore, we have 0.037 amps. What is an amp? An amp is 1 coulomb of charge moving per second. Therefore, we can restate our answer as being 0.037 coulombs of charge moving each second.

However, our question asked about how much has moved after 1 *minute*. Since there are 60 seconds in each minute, we can multiply 0.037 by 60 for our answer. $0.037 * 60 = 2.22$ So, after 1 minute, 37 milliamps of current moves 2.22 coulombs of charge.

3.3 AC vs. DC Current

You may have heard the terms AC or DC when people talk about electricity. What do those terms mean? In short, DC stands for **direct current** and AC stands for **alternating current**. So far, our descriptions of electricity have dealt mostly with DC current. With DC current, electricity makes a route from the positive terminal to the negative. It is the way most people envision electricity. It is "direct."

However, DC current, while great for electronics projects, very quickly loses power over long distances. If we were to transmit current that simple flows from the positive to the negative throughout the city, we would have to have power stations every mile or so.

So, instead of sending current in through one terminal and other through another, with alternating current, the positive and negative sides make a complete switch (both back and forth) 50–60 times per second. So, the electrons switch back and forth, over and over again, which direction they are moving. It is like someone is pushing and pulling current back-and-forth. In fact, at the generator station, that is exactly what is going on! This may seem strange, but this push and pull action allows much easier power generation and allows much more power to be delivered over much longer distances.

AC current such as the current that comes out of a wall socket is much more powerful than we require for our projects here. In fact, converting high-power AC current to low-power DC voltage used in electronic devices is an art in itself. This is why companies charge so much money for battery chargers—it takes a lot of work to get one right!

Now, not all AC current is like this. We call this current AC "mains" current, because it comes from the power mains from the power stations. It is supposed to operate at about 120 volts and the circuits are usually rated for about 15–30 amps (that's 15,000–30,000 milliamps). That's a lot of electricity!

In addition to AC mains current, there are also AC currents which we will call AC "signal" current. These currents come from devices like microphones. They are AC because they do alternate. When you speak, your voice vibrates the air back-and-forth. A microphone converts these air vibrations into small vibrations of electricity—pushing and pulling a small electric current back and forth. However, these AC currents are so low-powered as to be almost undetectable. They are so small, we have to actually amplify these currents just to work with them using our DC power!

So, in short, while we will do some work with AC voltages later in the book, all of our projects will be safe, low-power projects. We will often touch wires with our projects active, or use multimeters to measure currents and voltages in active circuits. This is perfectly safe for battery-operated projects. But *do not* attempt these same maneuvers for anything connected to your wall outlet unless you are properly trained.

3.4 Which Way Does Current Flow?

One issue that really bungles people up when they start working with electronics is figuring out which way that electrical current flows. You hear first that electrical current is the movement of electrons, and then you hear that electrons move from negative to positive. So, one would naturally assume that current flows from negative to positive, right?

Good guess, but no. Current is not the flow of physical stuff like electrons, but the flow of *charge*. So, when the chemical reaction happens in the battery, the positive side gets positively charged. The electrons are a negative charge that moves toward the positive charge. The positive charge is just as real as the electron charge, even though physical stuff isn't moving.

Think about it this way. Have you ever used a vacuum cleaner? Let's say we are building a vacuum cleaner. Where do you start? Usually, you start at the inside where the suction happens and then trace the flow of suction through the tubes. Then, at the end of the tube, the dust comes into tube.

Engineers don't trace their systems from the dust to the inside, they trace their systems from the suction on the inside out to the dust particles on the outside. Even though it is the dust that moves, it is the suction that is interesting.

Likewise, for electricity, we usually trace current from positive to negative even though the electrons are moving the other way. The positive charge is like the suction of a vacuum, pulling the electrons in. Therefore, we want to trace the flow of the vacuum from positive to negative, even though the dust is moving the other way.

The idea that we trace current from positive to negative is often called **conventional current flow**. It is called that way because we conventionally think about circuits as going from the positive to the negative. If you are tracing it the other way, that is called **electron current flow**, but it is rarely used.

Review

In this chapter, we learned:

1. Electric current is the flow of charge.
2. Charge is measured in coulombs.
3. Electric current flow is measured in coulombs per second, called amperes or amps.
4. A milliampere is one thousandth of an ampere.
5. In an atom, protons are positively charged, electrons are negatively charged, and neutrons are neutrally charged.
6. Batteries work by having a chemical reaction which causes electricity to flow through wires.
7. In DC current, electricity flows continuously from positive to negative.
8. In AC current, electricity flows back and forth, changing flow direction many times every second.
9. Even though electrons flow from negative to positive, in electronics we usually think about circuits and draw circuit charges as flowing from positive to negative.
10. AC mains current (the kind in your wall outlet) is dangerous, but battery current is relatively safe.
11. Small signal AC current (like that generated by a microphone) is not dangerous, either.

Apply What You Have Learned

1. If I have 56 milliamps of current flowing, how many amps of current do I have flowing?
2. If I have 1,450 milliamps of current flowing, how many amps of current do I have flowing?
3. If I have 12 amps of current flowing, how many milliamps of current do I have flowing?
4. If I have 0.013 amps of current flowing, how many milliamps of current do I have flowing?
5. If I have 125 milliamps of current flowing for one hour, how many coulombs of charge have I used up?
6. What is the difference between AC and DC current?
7. In AC mains current, how often does the direction of current go back and forth?
8. Why is AC used instead of DC to deliver electricity within a city?
9. In working with electronic devices, do we normally work in amps or milliamps?

Chapter 4

Voltage and Resistance

In the previous chapter we learned about current, which is the rate of flow of charge. In this chapter we are going to learn about two other fundamental electrical quantities—**voltage** and **resistance**. These two quantities are the ones that are usually the most critical to building effective circuits.

Current is important because limiting current allows us to preserve battery life and protect precision components. Voltage, however, is usually the quantity that has to be present to do any work within a circuit.

4.1 Picturing Voltage

What is voltage? Voltage is the amount of power each coulomb of electricity can deliver. If you have a one coulomb of electricity at 5 volts and I have one coulomb of electricity at 10 volts, that means that my coulomb can deliver twice as much power as yours.

A good analogy to electronics is the flow of water. When comparing water to electricity, *coulombs* are a similar unit to *liters*—coulombs measure the amount of electrical charge present just like a liter is the amount of water stuff present. Both charge and water both flow. In water, we can measure the flow of a current of a stream in liters-per-second. Likewise, in electronics, we measure the flow of charge through a wire in coulombs-per-second, called amperes.

Now, I want you to image the end of a hose containing water. Normally, the water just falls out of the hose, especially if the hose is just sitting on the ground. That hose just sitting on the ground is like a current with zero volts—each unit of water or charge is just not doing that much.

Let's pretend we added a spray nozzle to the hose. What happens now? Water shoots out of the nozzle. We haven't added any more water—it is actually the same amount of current flowing. Instead, we increased the pressure on the water, which is just like increasing the voltage on an electric charge. By increasing the pressure, we changed the amount of work that each liter of water is available to perform. Likewise, when we increase voltage, we change the amount of work that each coulomb of electricity can do.

One way we might measure the pressure of water coming out of a hose is to measure how far up it can shoot out of the hose. By doubling the pressure of the water, we can double how far out of the hose it can shoot. Similarly, with voltages, large enough voltages can actually jump air gaps across circuits. However, to do this, it takes a lot of voltage—about 30,000 volts per inch of gap. If you have been shocked by static electricity, though, this is what is happening! The power of the charge was extreme (thousands of volts), but the amount of charge in those shocks are so small that it doesn't harm you (about 0.00000001 coulombs).

4.2 Volts are Relative

While charge and current are fairly concrete ideas, voltage is a much more relative idea. You can actually never measure voltage absolutely. All voltage measurements are actually relative to other voltages. That is, I can't actually say that my electric charge has exactly 1, 2, 3, or whatever volts. Instead, what I have to do is say that one charge is however many volts more or less than another charge. So, let's take a 9-volt battery. What that means is not that the battery is 9 volts in any absolute sense, but rather that there is a 9-volt *difference* between the charge at the positive terminal and the charge at the negative terminal. That is, the pressure with which charge is trying to move from the positive terminal to the negative terminal is 9 volts.

4.3 Relative Voltages and Ground Potential

When we get to actually measuring voltages on a circuit, we will only be measuring voltage *differences* on the circuit. So, I can't just put a probe on one place on the circuit, I have to put my probe on two different places on the circuit and measure the voltage difference (also called the **voltage drop**) between those two points.

However, to simplify calculations and discussions, we usually choose some point on the circuit to represent "zero volts." This gives us a way to standardize voltage measurements on a circuit, since they are all given relative to the same point. In theory this could be any point on the circuit, but, usually, we choose the negative terminal on the battery to represent zero volts.

This "zero point" goes by several names, the most popular of which is **ground** (often abbreviated as **GND**). It is called the ground because, historically, the physical ground has often been used as a reference voltage for circuits. Using the physical ground as the zero point allows you to also compare voltages between circuits with different power supplies. However, in our circuits, when we refer to the ground, we are referring to the negative terminal on the battery, which we are designating as zero volts. If we designate any other part of the circuit as a ground, we will let you know.

Another, lesser-used term for this designated zero volt reference is the **common** point. Many multimeters label one of their electrodes as **COM**, for the common electrode. When analyzing a circuit's voltage, this electrode would be connected to whatever your zero-volt point is.

This "ground" analogy also makes sense with our water hose analogy. Remember that a voltage is the potential for a charge to do work. What happens to water after it lands on the ground? By the time the water from my hose lands on the ground, it has lost all its energy. It is just sitting there. Sure, it may seep or flow around a bit, but nothing of consequence. All of its ability to do work—to move quickly or to knock something over—has been drained. It is just on the ground. Likewise, when our electric charge is all puttered out, we say that it has reached "ground potential."

So, even though we could designate any point as being zero, we usually designate the negative terminal of the battery as the zero point, indicating that by the time electricity reaches that point, it has used up all of its potential energy—it now has zero volts.

4.4 Resistance

Resistance is how much a circuit or device resists the flow of current. Resistance is measured in **ohms**, and is usually represented by the symbol **Ω**. Going back to our water hose analogy, **resistance** is how small the hose is. Think about a 2-liter bottle of pop. The bottle has a wide base, but the opening is small. If I turn the bottle upside down, the small opening limits the amount of liquid that flows out at one time. That small opening is giving *resistance* to the flow of liquid, making it flow more slowly. If you cut off the small opening, leaving a large opening, the liquid will come out much faster because there is less resistance.

Ohm's law, which we will use throughout this book, tells us about the relationship between resistance, voltage, and current flow. The equation is very simple. It says:

$$V = I * R \tag{4.1}$$

In this equation, V stands for voltage, I stands for current (in *amperes*, not milliamperes), and R stands for resistance (in ohms). To understand what this equation means, let's think again about water hoses. The water the comes out of the fawcet of your house has essentially a constant current. Therefore, according to the equation, if we add resistance, it will increase our voltage.

We know this to be true from experience. If we have a hose and just point it forward, water usually comes out about a foot or two. Remember, voltage is how much push the water has, which determines how far the water will go when it leaves the hose. However, if my children are on the other side of the yard, and I want to hit them with a water spray, what do I do? I put my thumb over the opening. This increases the resistance, and, since the current is constant, the voltage (the distance the water will travel after it leaves the hose) will increase.

However, in circuits, we usually don't have a constant current source. Instead, batteries provide a constant voltage source. A 9-volt battery will provide 9-volts in nearly every condition. Therefore, for electronics work, we usually rearrange the equation a little bit. Using a little bit of algebra, we can solve our equation for either current or resistance, like this:

$$I = V/R \tag{4.2}$$

$$R = V/I \tag{4.3}$$

Equation 4.2 is the one that is usually most useful. To understand this equation, think back to the example of the bottle turned upside down. There, the liquid has a constant amount of push/voltage (from gravity), but we had different resistances. With the small opening, we had a large resistance, so the water came out slower. With the large opening, we had almost no resistance, so the water came out all at once.

Example 4.4 Let's put Ohm's law to use. If I have a 5-volt voltage source with 10 ohms of resistance, how much current will flow? Since we are solving for current, we should use equation 4.2. This says $I = V/R$. Therefore, plugging in our voltage and resistance, we have $I = 5/10$, which is $I = 0.5$amperes (remember, Ohm's law always uses amperes for current). Note that, in this book, we will never use fractions when we solve problems, we will only use decimals.

Example 4.5 Now let's say that we have a 10 volt source, and we want to have 2 amps worth of current flowing. How much resistance do we need in order to make this happen? Since we are now solving for resistance, we will use equation 4.3, which says $R = V/I$. Plugging in our values, we see that $R = 10/2 = 5\Omega$. Therefore, we would need 5Ω of resistance.

Example 4.6 Now let's say that I have a 9-volt source and I want to limit my current to 10 *milliamps*. This uses the same equation, but the problem I have is that my units are in milliamps, but my equation uses amps. Therefore, before using the equation, I have to convert my current from milliamps to amps. Remember, to convert milliamps to amps, we just divide by 1000. Therefore, we take 10 milliamps and divide by 1000, we get 0.010 amps. Now we can use equation 4.3 to find the resistance we need. $R = V/I = 9/0.010 = 900\Omega$. Therefore, with 900 Ω of resistance, we will limit our current to 10 milliamps.

Review

In this chapter, we learned:

1. Voltage is the amount of power that each unit of electricity delivers.
2. The volt is the electrical unit that we use to measure voltage.
3. Voltage is always given relative to other voltages—it is not an absolute value.
4. The ground of a circuit is a location on the circuit where we have chosen to use as a universal reference point—we define that point as having zero voltage for our circuit to make measuring other points on our circuit easier.
5. In DC electronics, the chosen ground is usually the negative terminal of the battery.
6. Other terms and abbreviations for the ground include common, GDN, and COM.
7. Resistance is how much a circuit resists the flow of current and is measured in ohms (Ω).
8. Ohm's law tells us the relationship between voltage, current, and resistance: $V = I * R$.
9. Using basic algebra, we can rearrange ohm's law in two other ways, depending on what we want to know. It can be solved for current, $I = V/R$, or it can be solved for resistance, $R = V/I$.

Apply What You Have Learned

1. If I have a 4-volt battery, how many volts are between the positive and negative terminals of this battery?
2. If I choose the *negative* terminal of this battery as my ground, how many volts are at the *negative* terminal?
3. If I choose the *negative* terminal of this battery as my ground, how many volts are at the *positive* terminal?
4. If I choose the *positive* terminal of this battery as my ground, how many volts are at the *negative* terminal?
5. Given a constant voltage, what effect does increasing the resistance have on current?
6. Given a constant current, what effect does increasing the resistance have on voltage?
7. If I have a 10-volt battery, how much resistance would I need to have a current flow of 10 amps?
8. If I have a 3-volt battery, how much resistance would I need to have a current flow of 15 amps?
9. Given 4 amps of current flow across 200 ohms of resistance, how much voltage is there in my circuit?

10. If I am wanting to limit current flow to 2 amps, how much resistance would I need to add to a 40-volt source?

11. If I am wanting to limit current flow to 2 milliamps, how much resistance would I need to add to a 9-volt source?

Chapter 5

Your First Circuit

In the last two chapters we have learned about the fundamental units of electricity—charge, current, voltage, and resistance. In this chapter, we are going to put this information to use in a real circuit.

5.1 Circuit Requirements

For a circuit to function properly, you usually need several things:

1. A source (usually providing a constant voltage) which provides electricity for your circuit
2. A network of wires and components that ultimately lead from your voltage source to ground (which is usually the negative terminal on the battery)
3. Some amount of resistance in your circuit

We need the source because, without a source, we don't have any power to move electricity around! If we have a circuit, but no source, it will just sit there. In our circuits, batteries will usually provide the power we need.

We need the wires because, unless we provide a *complete pathway* from a higher voltage to a lower voltage, the electricity won't move. If we want electricity to move, we have to make a pathway from a higher voltage to a lower voltage. Without this pathway, we have what is known as an **open circuit**. No electricity flows in an open circuit.

However, in addition to the wires, we must also have resistance. Without resistance, the current would be too high. It would be so high that it would immediately drain your battery, and likely destroy all of your components that you have connected. You can actually see this using Ohm's law. If we have a 10-volt source with no resistance, the current is given by the equation $I = V/R = 10/0$. Dividing by zero gives you, essentially, infinite current. Now, wires and batteries themselves have some resistance, so the current wouldn't be infinite, but it would be very, very large and would quickly drain your battery and destroy any sensitive components you had connected. Therefore, every pathway from the positive side of the battery to the negative *must* have some amount of resistance. When a pathway from positive to negative occurs without resistance, this is known as a **short circuit**.

In other words, to accomplish real tasks with electricity, we must control its flow. If it doesn't flow (as in an open circuit), it can't do anything. If it flows without resistance (as in a short circuit), it does damage rather than work. Therefore, the goal of electronics is to provide a controlled route so that the power of electricity does the things we want it to do on its way from positive to negative.

5.2 Basic Components

The first circuits that we will build will only use three basic types of components:

- Batteries (9-volt)
- Resistors
- LEDs

As we have discussed before, batteries provide a constant amount of voltage between the positive and negative terminals. A 9-volt battery, therefore, will always have a 9-volt difference between the positive and negative terminals.

A resistor is a device that, as its name implies, adds resistance to a circuit. Resistors have colors that indicate how much resistance they add to the circuit. You don't need to know the color codes yet, but if you are curious you can see Appendix B.1. So, if we want to add 100Ω to our circuit, we just find a resistor with a value of 100Ω. Resistors are not the only devices that add resistance to a circuit, but they are usually what are used when you want to add a fixed amount of resistance. Resistors have two sides, but they both function identically—there is no backwards or forwards for a resistor. You can put them in your circuit either way and they will function just fine.

Of the components in this section, the LED is probably the strangest. LED stands for light-emitting diode. A diode is a component that only allows current to flow in one direction. It blocks the flow of electricity in the other direction. However, more importantly, LEDs emit light when current passes through them. However, LEDs do not resist current, so they must be used with a resistor to limit the amount of current flowing through them (most of them will break at 20–30 milliamps). Also, since LEDs only allow current to flow one way, they have to be wired in the right direction. The legs of an LED are different lengths. The longer leg of the LED should be on the more positive side of the circuit.

Most of your components (especially your resistors) come with very long legs. You can feel free to bend or cut these legs however you please to better fit in your circuit. However, on LEDs (and any other component where leg length matters), be sure to keep the longer legs longer so you don't get confused about which leg is the positive leg.

Figure 5.1: Wrapping the Resistor around the LED's Short Leg

FIXME—**Need picture here**

5.3 Creating Your First Circuit

Now we will put together a simple first circuit. What you will need is:

- 1 9-volt battery
- 1 red LED (other colors will work, too)
- 1 500Ω resistor (anything from 400 ohms to 1,000 ohms should work)

Even if you can't read the color codes on the resistor, you should be able to buy them with the value you want. To make this circuit, take one leg of the resistor and twist it together with the *short* leg of the LED. It should look like Figure 5.1.

Now, take the long leg of the LED and touch it to the positive terminal of the battery. Nothing happens—why not? Nothing happens because even though we have connected the wires to the positive side of the battery, the electricity has nowhere to go to. We have an open circuit because there is not a complete path from positive to negative.

Now, touch the long leg of the LED to the battery and, at the same time, touch the unattached end of the resistor to the battery. The LED should give a nice glow of its color. Congratulations—you have built your first circuit!

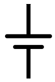
Even though we can't see the electricity moving, I hope you can see how it will flow through the circuit. We can trace the current flow from the positive terminal of the battery through the LED. The resistor limits the amount of current flowing through the circuit, and therefore through our LED (the resistor can actually go on either side of the LED, it will limit the flow no matter which side it is on). Without the resistor, the battery would easily go over the 30 milliamp rating of our LED and it would no longer work. If you connected it without a resistor, you might see it turn on for a moment and then very quickly turn off, and then it would never work again. If you have an extra LED you can try this out if you want. It is not dangerous it will just cost you the price of an LED.

If your LED is backwards, no current will flow at all. It won't hurt the LED, but it won't turn on unless it is oriented in the right direction.

5.4 Adding Wires

We are not going to physically add wires to our circuit at this time, but I did want to make a note on wires. Changing the lengths of wires will not affect our circuits in any way. For some high-precision circuits, or some very long wires, the length of a wire will have some effect on these circuits. We are not doing any

Figure 5.2: Basic Component Diagram Symbols

Symbol	Component	Description
	Battery	A battery is represented by a long line and a short line stacked on top of each other. Sometimes, there are two sets of long and short lines. The long line is the positive terminal and the short line is the negative terminal (which is usually used as the ground).
	Resistor	A resistor is represented by a sharp, wavy line with wires coming out of each side.
	LED	An LED is represented by an arrow with a line across it, indicating that current can flow from positive to negative in the direction of the arrow, but it is blocked going the other way. The LED symbol also has two short lines coming out of it, representing the fact that it emits light.

high-precision circuits, and our wire lengths are all less than a meter. Therefore, for the electronics we are doing, we can totally ignore wire length.

Therefore, if we connected our components using wires rather than directly wrapping their legs around each other directly, it would have no effect on the circuit at all. What is important is not the wires but the connections—what components are connected together and how are they connected. The length of wire used to connect them is not important.

5.5 Drawing Circuits

So far, we have only described circuits in words or by showing you pictures. This, however, is a lousy way of describing circuits. In complicated circuits, trying to trace the wires in a photograph is difficult. If you wanted to draw a circuit that you wanted built, you would have to be an artist to render it correctly. Likewise, reading through text describing a circuit takes a long time and is easy to get lost for large circuits.

Therefore, in order to communicate information about how a circuit is put together in a way that is easy to read and write, engineers have developed a way of drawing circuits called **circuit diagrams** or **electronic schematics** (often shortened to just *diagram* or *schematic*). In a circuit diagram, each component is represented by an easy-to-draw symbol that helps you remember what the component does. Figure 5.2 shows the symbols for the components we have used so far. Note that everybody draws the symbols slightly differently, and some components have more than one symbol. However, these are the symbols we will use in this book. For more symbols, see Appendix C.

Then, the components are connected together using lines to represent the wires and connections between the components.

Figure 5.3: Basic LED Circuit Drawn as a Diagram

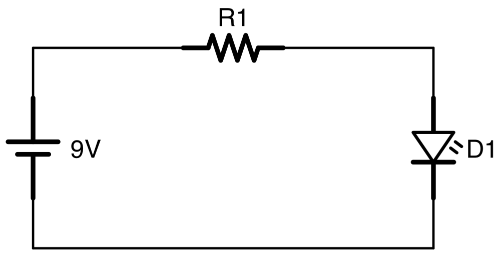
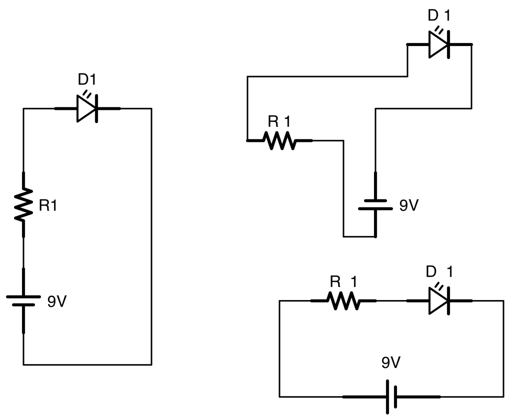


Figure 5.4: Alternative Ways of Drawing the Basic LED Circuit



Therefore, we can redraw our original circuit using these symbols like you see in Figure 5.3.

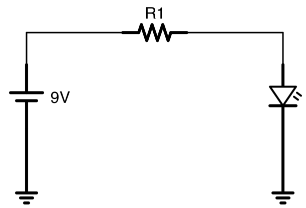
Notice that each of our components are laid out on the diagram with wires connecting them. Remember that it doesn't matter if we have very long wires, very short wires, or if the components are directly placed end-to-end—the resulting circuits will operate identically. Also notice that each component is labeled (R1 and D1) because, as we make more complicated circuits, it is important to be able to refer back to them.

It does not matter in a diagram which way you have your components turned, how long or short your wires are, or what the general spacing looks like. When you actually wire it, all of those things will change. The important part of a circuit diagram is to convey to the reader what the parts are, how they are connected, and what the circuit does in the way that is easiest to read.

For instance, all of the circuits in Figure 5.4 are equivalent to the circuit in Figure 5.3, they are just drawn differently.

For consistency, I like to draw all of my batteries to the left of the drawing with the positive side on top.

Figure 5.5: Basic LED Circuit Drawing Using the Ground Symbol



By keeping the battery positive-side-up, components with higher voltage are usually closer to the top, and components with lower voltages are usually closer to the bottom, with the ground (i.e., zero volts) coming back into the negative terminal. I also try to make my wire lines as simple as possible in order to make following them easier.

By keeping some amount of consistency, it is easier to look at a drawing and see what it happening.

5.6 Drawing the Ground

Remember that for electricity to move, every circuit must be fully connected from the positive side to the negative side. That means that in larger circuits there are numerous connections that come from the positive or go back to the ground/negative. Because of this, a special symbol has been adopted to refer to the ground point in a circuit. This symbol, the ground symbol, has three lines, each shorter than the next. Every point on a circuit that has this symbol connected to it is connected to each other (usually they are all connected to the negative side of the battery).

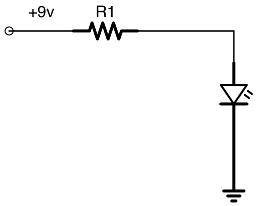
Therefore, the circuit in Figure 5.5 is the same circuit as before, just drawn using the ground symbol. Since every point with the ground symbol are all connected together, using this symbol on both the negative terminal and the negative side of the LED means that they are wired together.

This doesn't help us a lot for this circuit (and, in fact, it makes it a little less easy to read). However, in complex circuits, it is much easier to write the ground symbol than trying to have twenty lines drawn back to the negative terminal.

Additionally, the same is true with the positive side of the battery. Many components require a direct connection to a specific voltage to work correctly. These are usually marked with just a disconnected wire with the end of the wire marking what voltage it requires. We make less use of that symbol in this book than the ground symbol, but it does come in handy sometimes.

So, using both the voltage source and the ground symbols, we could rewrite the same circuit again in the manner shown in Figure 5.6. This circuit, again, is not *wired* any differently than before. We are just *drawing* it differently. For this circuit, it doesn't matter, but in more complex circuits, if we need a specific voltage at a specific location, this symbol tells us to put it there.

Figure 5.6: Simple LED Circuit Using Positive and Ground Symbols



Review

In this chapter, we learned:

1. Every circuit requires a source of power (usually a battery), wires and components, some amount of resistance, and a complete path back to the negative side of the power source.
2. An open circuit is one that does not connect back to the negative side (and thus does not provide any electricity), and a short circuit is one that connects back to the negative side without any resistance (and thus overwhelms the circuit with current).
3. Batteries supply a fixed voltage between its two terminals.
4. A resistor provides a fixed resistance (measured in ohms) within your circuit.
5. An LED allows current to flow in only one direction, gives off light when current is flowing, but is destroyed when the current goes above 20–30 milliamps.
6. The longer leg of the LED should be on the positive side of the circuit.
7. Wires on a circuit can be almost any length (from zero to a few meters) without changing the functionality of the circuit.
8. A circuit diagram is a way of drawing a circuit so that it is easy to read and understand what the circuit is doing.
9. Each component has its own symbol in a circuit diagram.
10. Every component labeled with the ground symbol is connected together, usually at the negative side of the battery.
11. Voltage sources can be similarly labeled by a wire connected on one side labeled with the voltage that it is supposed to be carrying.

Apply What You Have Learned

Special Note - In the problems below, since we have not yet studied LED operation in-depth, we are ignoring the electrical characteristics of the LED and just focusing on the resistor. If you know how to calculate the circuit characteristics using the LED, please ignore it anyway for the purpose of these exercises.

1. Calculate the amount of current running in the circuit you built in this chapter using Ohm's law. Since Ohm's law gives the results in amps, convert the value to milliamps.
2. Let's say that the minimum amount of current needed for the LED to be visibly on is 1 milliamp. What value of resistor would produce this current?
3. Let's say that the maximum amount of current the LED can handle is 30 milliamps. What value of resistor would produce this current?
4. Draw a circuit diagram of a short circuit.
5. Take the circuit drawing in this chapter, and modify it so that it is an open circuit.
6. Draw a circuit with just a battery and a resistor. Make up values for both the battery and the resistor and calculate the amount of current flowing through.

Chapter 6

Constructing and Testing Circuits

In the previous chapter, we learned the theory behind how to analyze circuits. In this chapter, we are going to put real circuits together and use simple equipment to analyze the same kinds of problems, and compare our calculated answers to the measurements we make on live circuits.

6.1 The Solderless Breadboard

The most important piece of equipment to use for making circuits is the **solderless breadboard**. Before solderless breadboards, if you wanted to put together a circuit, you had to attach them to a physical piece of wood to hold them down, and then **solder** the pieces together. Soldering is a process where two wires are physically joined using heat and a type of metal called solder, which melts at much lower temperatures than other types of metal. So, what you would have to do is attach the electrical components to the board, wrap the components' legs around each other, and then heat them up with a soldering iron and add solder to join them permanantly.

This was an involved process, and, though it was possible to get your components back, you were generally stuck with your results. The solderless breadboard is an amazing invention that allows us to quickly and easily create and modify circuits without any trouble at all. Figure 6.1 shows what a solderless breadboard looks like.

The solderless breadboard has a number of spring clips (usually about 400 or 800 of them) called **connection points** which will allow you to insert wires or component leads and will hold them in place. Not only that, the breadboard itself will connect the components for you!

The way that this works is that the breadboard is broken up into little half-rows called **terminal strips**. Each terminal strip has multiple connection points—usually five. Each connection point on a given terminal strip is connected by wire *inside* the breadboard. Therefore, to connect two wires or leads together, all you need to do is connect them to the same terminal strip. Any two wires or leads connected to the same

Figure 6.1: A Solderless Breadboard

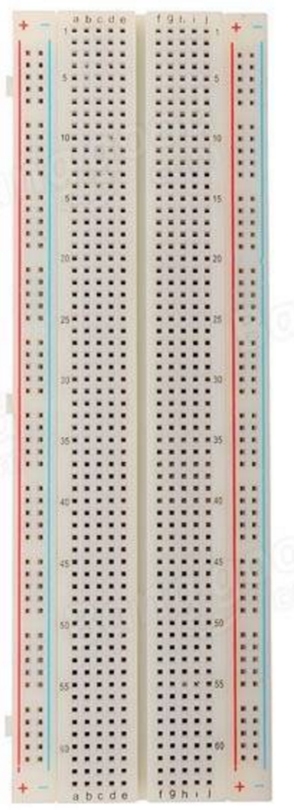
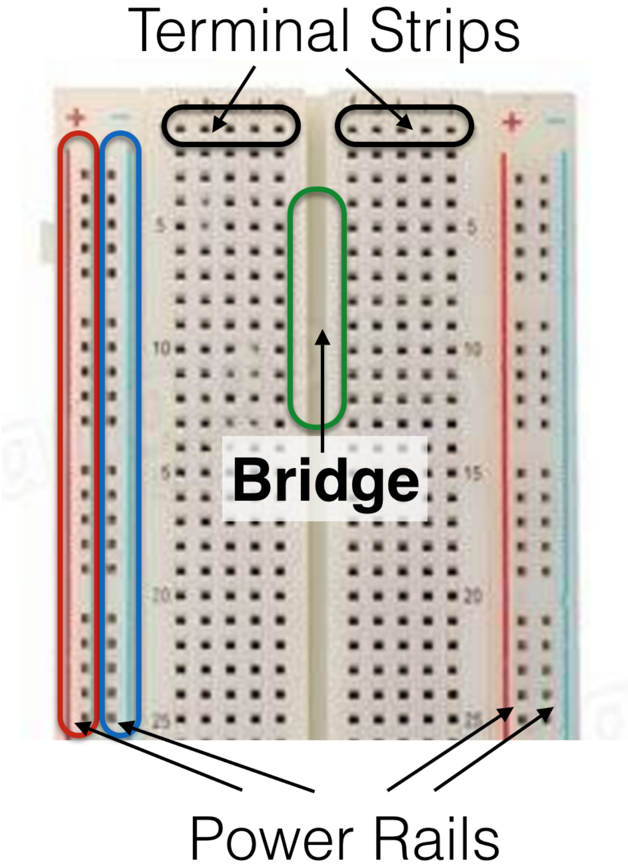


Figure 6.2: Parts of a Solderless Breadboard



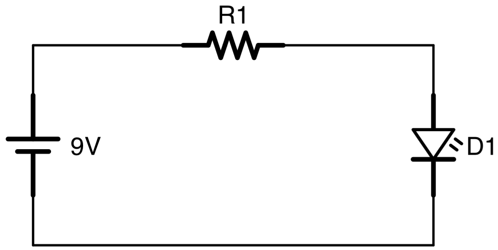
terminal strip are themselves connected.

In most breadboards, the two sides of the breadboard are separated by a gulf known as the **bridge**. The bridge is a visual indication that the two sets of terminal strips are not connected, but it also serves a practical purpose. If you have an integrated circuit (a small chip), the bridge is the right width so that you can place your integrated circuit right over the bridge, and each leg of the chip will receive its own terminal strip for you to easily connect them to what you need. We will cover this in more depth in later chapters.

In addition to the terminal strips, most breadboards have two strips running down each side, one with a red line and one with a blue line. These are known as **power rails** (some people call them **power buses**).

Power rails are very similar to terminal strips, with a few exceptions. The main difference is that, in terminal strips, only the five connection points grouped together are connected. On power rails, all of the connection points all the way down the board are connected together, even when there are short gaps. The positive and negative are *not* connected to each other (that would create a short circuit), and they are *not* connected to the power rails on the other side of the board (unless you connect them manually).

Figure 6.3: Basic LED Circuit



In many projects, many components need direct access to the positive or negative power supply. Power rails make this easy by simply connecting these rails all the way down the board. If you plug your power source's positive and negative terminals into the positive and negative rails on the breadboard, then any time you need a connection to the positive or negative terminal, you can just bring a wire to the closest connection point on the power rail.

6.2 Putting a Circuit Onto a Breadboard

To see how a simple circuit works on a breadboard, let's go back to the circuit we first looked at in Chapter 5. Figure 6.3 has the drawing again for ease of reference.

So, how do we translate what we see in the drawing to what we need to put in the breadboard? Well, let's take a look at what is in the circuit—a 9-volt battery, an LED, and a resistor. Let us not concern ourselves with the battery at the moment. So, without the battery, we have a resistor connected to an LED.

Let us start out by simply placing our components onto the breadboard. What you will want is to place them on the breadboard so that each of their legs are on *different* terminal strips. It doesn't matter *which* terminal strips you use—just make sure the legs all get plugged into different ones. Figure 6.4 shows how your breadboard should look so far. Note that the longer leg of the LED is closer to the resistor.

Figure 6.5 shows the *wrong* way to do it. In that figure, the both of the legs of the components are on the same row, which is the same thing as placing a wire between the legs, creating a short circuit. Don't do that! Make sure each leg goes into its own row.

Now, to connect the resistor to the LED, we need to add a wire. So, all we need to do is connect a wire to any empty connection point that is on the same terminal strip of the right leg of the resistor, and connect the other side of that wire to the left leg of the LED as shown in Figure 6.6.

A common mistake that people will make is to connect the wire to the row right before or after the component. Take some time and be extra certain that the wire is connected to the same row as the leg of your components.

Figure 6.4: Putting the Components onto the Breadboard

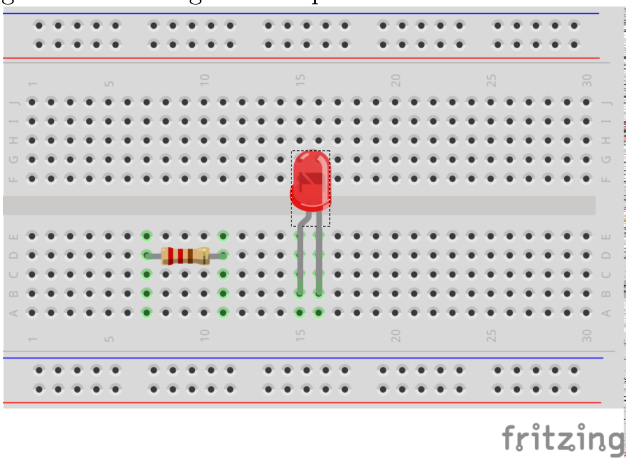


Figure 6.5: The Wrong Way to Put Components onto the Breadboard

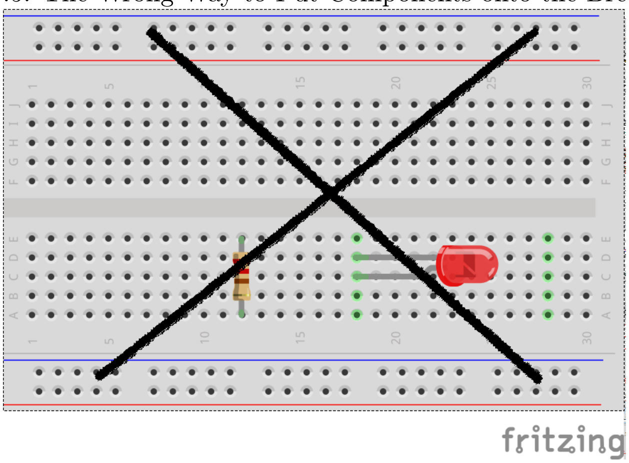
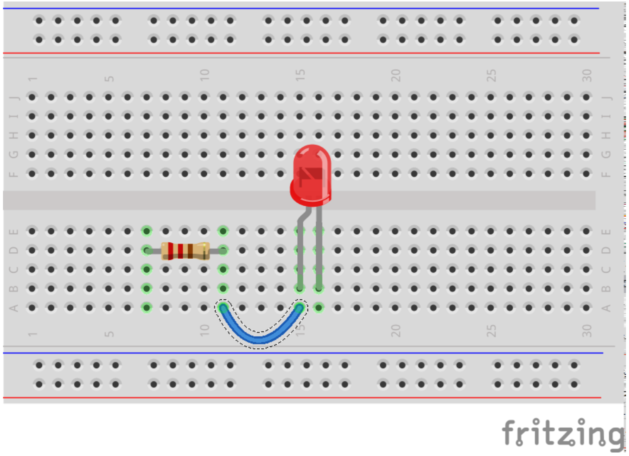


Figure 6.6: Adding a Wire to Connect the Components



Now, we need to connect our project to the power rails. So, take a red wire from the left leg of the resistor to the positive power rail (remember, as long as it is in the same terminal strip as the resistor, they will be connected). Likewise, take a black wire from the right leg of the LED to the negative power rail. I always use red wires for connecting to the positive power rail, and black wires for connecting to the negative/ground rail, as it makes it more clear when I am looking at my project what wire carries what. Your project should look like Figure 6.7.

Now your project is almost done. All you need to do now is to connect your power rails to a power supply. Connect a T-connector to a 9-volt battery, and then connect the red (positive) wire to the positive power rail on the breadboard. You can plug it in anywhere on the rail, but I usually connect the power to the edge of the rail to leave more room for components. Then, connect the black (negative) wire to the negative power rail on the breadboard. As soon as you do this, the LED should light up! Figure 6.8 shows the final circuit.

Note that many T-connectors for 9-volt batteries have very flimsy wires that are difficult to insert into a breadboard. Usually, as long as you can get both terminals in far enough to touch the metal within the connection point, it will work.

If your circuit doesn't work, here is a list of things to check:

1. Make sure your battery is properly connected to the breadboard—the red should go to positive and the black to negative.
2. Make sure there are *no* wires directly connecting positive to negative on the board. Any direct pathway from positive to negative without going through a component will cause a short-circuit and can destroy your components and battery.
3. Make sure that your wires are connected to the same terminal strip as the component lead that they are supposed to be connected to. If they are on a different row, *they are not connected*!

Figure 6.7: Adding Wires to the Power Rails

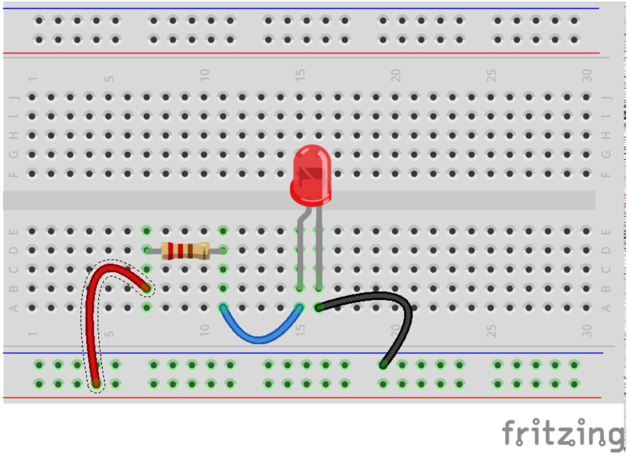


Figure 6.8: Final LED Circuit with Power Connected

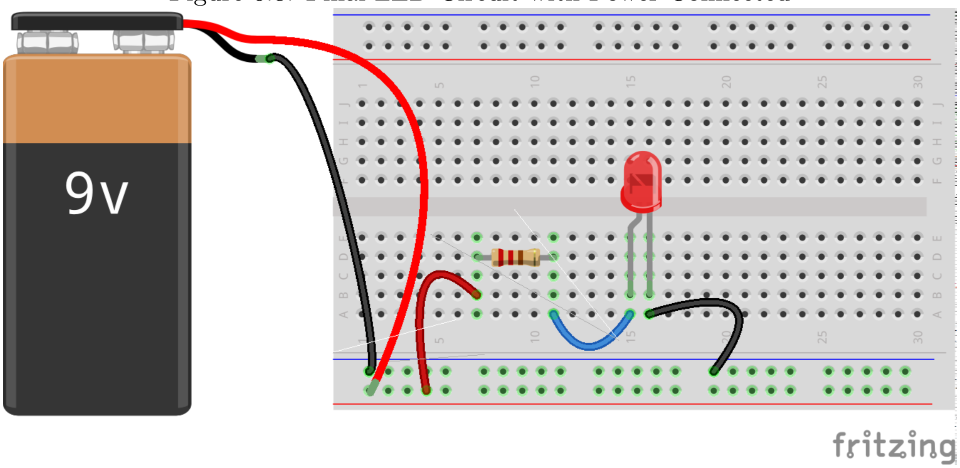
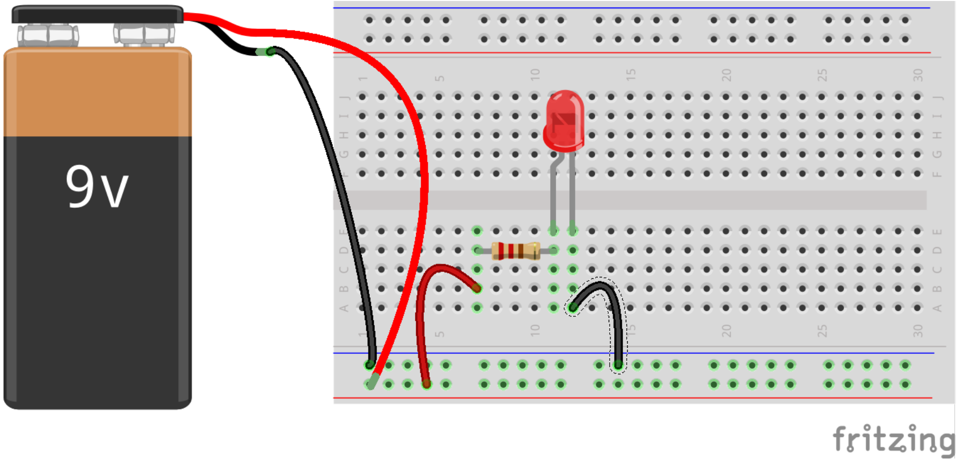


Figure 6.9: Joining Components by Putting Their Leads on the Same Terminal Strip



4. Make sure the LED is inserted in the right way. The longer leg should be connected to the resistor, and the shorter leg should be connected to the negative power supply.

5. Make sure your components are good. Try replacing your LED with another LED to make sure it works.

6. If all of those things fail, take a picture of your project and post it to the forum mentioned in Chapter 1. Someone will likely be able to spot your problem and/or lead you in the right direction. Many other forums are also available on the web for this.

6.3 Using Fewer Wires

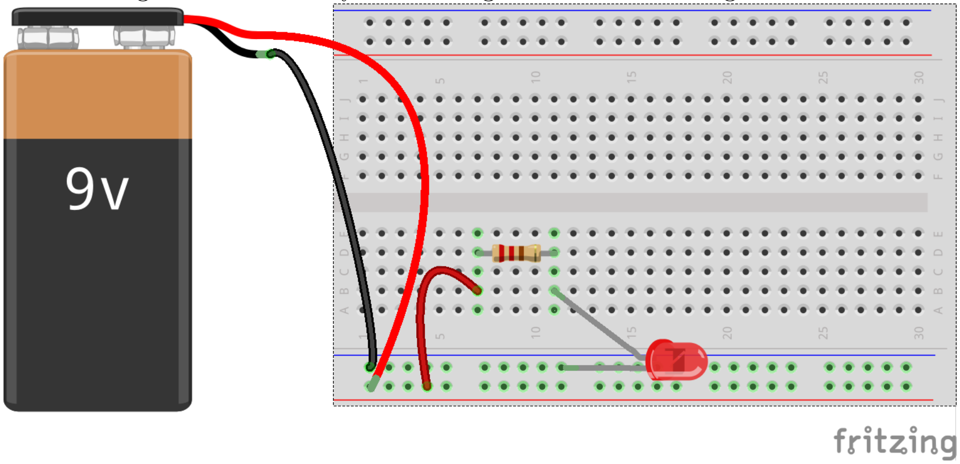
In the previous section, we used three wires to connect our components, plus two more wires from the battery. We can improve our project by reworking it so that most of the wires are not necessary.

Remember that any two leads or wires plugged in next to each on the same terminal strip are connected. Therefore, we can remove the wire that goes from the LED to the resistor simply by moving the LED and resistor so that the right leg of the resistor is on the same terminal strip. Figure 6.9 shows what this looks like.

However, that middle wire is not the only redundant wire. If you think about it, we could also save a wire by actually using the LED's own leads to go back to the negative rail. Figure 6.10 shows how this is setup. Now, in order to make the LED fit better, it is now on the *other* side of the resistor in the terminal strip. Remember that this does not matter at all! No matter where a component is connected on the terminal strip, it is joined with a wire to every other component on the same terminal strip.

Now, there is one last wire that we can get rid of. Can you think of which one it is? If you said the wire going from the positive rail to the resistor—you were right.

Figure 6.10: Directly Connecting the LED to the Negative Rail



What we can do is to directly connect the resistor to the positive rail. Doing this gives us what is shown in Figure 6.11.

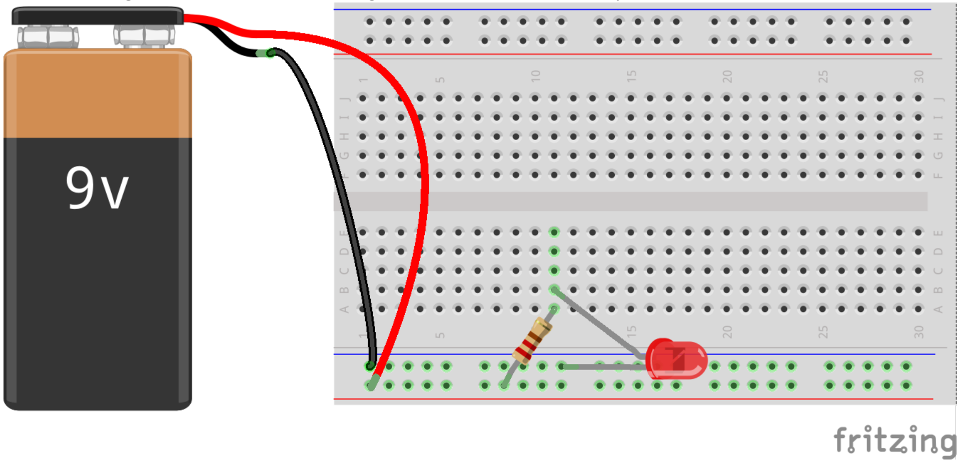
Therefore, as you can see, there are any number of ways that you can arrange parts on a breadboard to match a given schematic. All of these arrangements we have seen match the schematic given in Figure 6.3. As long as your circuit matches the configuration in the schematic, the specifics of where you put the wires and components is up to you. Some people like to place the components on their breadboard first, spaced out, and then add wires to connect them as needed. This works, though it does make for a messier board. Other people like to use as few wires as possible, and have their layouts as clean as possible (i.e., they don't like a tangled mess).

Some people like to use flexible jumper wires, that goes up and over the board. Other people like to use rigid jumper wires that lay down close to the board and is the exact length needed. The flexible wire allows more flexibility in building your circuits (they are easier to move around and reconfigure), while the solid, rigid wire makes the final result a lot cleaner and easier to follow.

You can also trim the legs of your components to make them fit better, if you want. Some people like to leave their components as intact as possible, while others like to trim the legs of their leads to be the exact right size for their project. However, if you do trim the leads on your LEDs, be sure to keep the positive leg longer!

However you like to work with electronics is up to you. There are lots of options, and they all end up with the same circuit.

Figure 6.11: Connecting the Resistor Directly to the Positive Rail



6.4 Testing Circuits with a Multimeter

Now that we know how to put circuits together, we need to know how to *test* our circuits. The main tool used to test simple circuits is the **multimeter**. It is called a multimeter because it measures *multi*ple different things about a circuit.

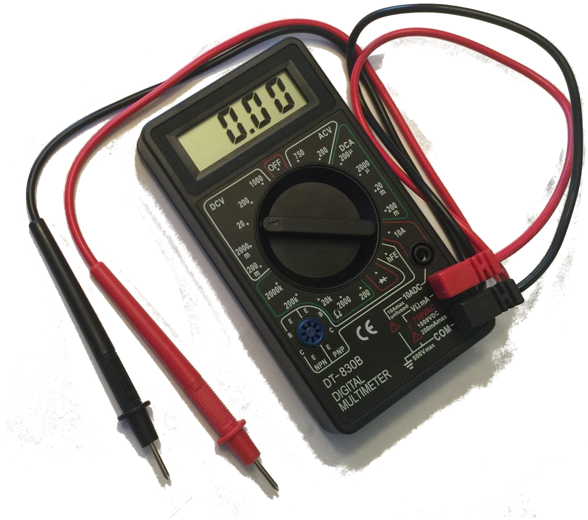
There are a lot of different multimeters around which have a lot of different functions. However, almost all of them will measure voltage, current, and resistance. Each of these values are measured by testing two different points on the circuit. Most multimeters have a red lead and a black lead. The red lead should connect to the more positive side of the circuit, and the black lead should connect to the more negative side of the circuit. However, if you get it reversed, it is usually fine—the multimeter may just report negative values if you are measuring for voltage or current.

To illustrate how to use a multimeter, we will start out measuring the voltage in a 9-volt battery. Remember from Chapter 4 that there is no absolute zero voltage—voltages are merely measured with reference to each other. Therefore, a multimeter doesn't tell you the exact voltage of something—there is no exact voltage. Instead, a multimeter allows you to choose two points on your circuit and measure the voltage difference (also known as the **voltage drop**) between them.

Now, remember that a 9-volt battery means that the battery should have 9 volts between its positive and negative terminals. Don't try it yet, but when we measure voltage, we will expect that the multimeter will tell us that the voltage difference is near 9 volts.

When using your multimeter, you must set *what* you are going to test *before* you test it. Otherwise, you can easily damage your multimeter or your circuit. Therefore, since we are going to measure voltage, select the DC Voltage setting on your multimeter (*do not* select the DC Current or DC Amperage setting!). If you are using a high-quality **auto-ranging** multimeter, that is all you need to do. However, when starting out, most people buy the bottom-of-the line multimeter. That's not a problem, but just know that you will probably accidentally break it at some point.

Figure 6.12: A Low-Cost Multimeter



If you are using a lower-quality multimeter, you will need to not only select *what* you want to measure, but the *estimated range* of values that you want to measure. On my multimeter, the DC Voltage has five different settings—`1000`, `200`, `20`, `2000m`, and `200m`. These are the upper boundaries (in volts) that these settings can read (though `2000m` and `200m` indicate millivolts). Additionally, they indicate the ranges that these settings are best at reading.

So, for a 9-volt battery, using the 1,000-volt setting is probably unwise. It may give a reading, but it probably won't be accurate. However, if I try it on too low of a setting (say, 2000m), it either won't read, or it will blow out my multimeter. So, the safe thing to do is to start with the highest reasonable setting (or just the highest setting if you don't know what's reasonable), test it, and the reduce the setting until it gives you a good reading.

So, for instance, for my 9-volt battery, let's say I didn't know the voltage. Therefore, I'm going to measure the battery using the 1,000-volt setting. After setting the multimeter to 1,000 volts, I will put the red lead on the positive terminal of the battery, and the black lead on the negative terminal. Be sure that you *firmly* press the *tip* of your leads against the positive and negative terminals. If it is not firm, or if you use the sides of your terminals, you will not get a good reading.

When I do this, my multimeter reads `9`.

Now, notice that this reading is significantly less than our 1,000-volt setting. Therefore, it may not be entirely accurate. So, I will reduce the setting to the 200-volt setting and measure again. This time, my multimeter reads `9.6`. This is definitely a more accurate reading—it is giving me an extra digit of accuracy! However, this reading is still significantly below the setting.

Therefore, I will reduce the setting again to the 20-volt setting and re-measure. This time, the measurement is `9.66`. Again, it is more accurate. Now, can I reduce the setting even more? Well, the next setting is

`2000m`, which is basically 2 volts. Our current reading is 9.66 volts, so it is above the cutoff point for the next setting. Therefore, I should not try it on a lower setting, both for the sake of accuracy and for the sake of my multimeter's lifespan.

However, I should note that if I did use a lower setting, since the setting is listed as being in millivolts (i.e., `2000m`), then the reading will also be in millivolts. That is, if we were to read the value of the battery on that setting, it would say `9660`, because that is how many millivolts the battery has.

Now, you could be wondering, why is a 9-volt battery anything other than exactly 9 volts? Well, it turns out that in electronics, no value is exact, and no formula works perfectly. When we talk about a 9-volt battery, we are actually talking about a battery that runs anywhere from 7 volts to 9.7 volts. In fact, my battery that started out at 9.66 volts will slowly lose voltage as it discharges. This is one of the reasons why measurement is so important.

Also, this means that in our circuits we will have to find ways to compensate for varying values. Our circuits should work across a wide range of possible values for our components. We will discuss strategies for this as we go forward.

The next thing we will measure is resistance. Pull out a resistor—any resistor. Appendix B.1 shows you how to find the resistor values based on the color bands on the resistor. I don't know about you, but my eyes are not that good at looking at those tiny lines on the resistor and figuring out which color is which. Many times, it is easier just to test it with the multimeter.

The process is the same as with measuring the voltage. First, find the resistance settings on your multimeter (perhaps just marked with the symbol for ohms—Ω). Start with the largest value (`2000k`) in my case (`k` means 1,000, so this is a 2,000,000 ohm setting). On this setting, the multimeter read `000`. So, I turned it down to the next setting, `200k`. This time, it read `00.2`. So, since the setting is listed in `k` (thousands), this means that the resistor is probably around 0.2 kΩ, or around 200 Ω. However, this is still not an accurate setting.

Next, I turned the dial down to the next setting, which is `20k`. When I read it this time, it said `0.22`, which would be about 220 Ω. Notice how, as the settings on the multimeter get closer to the actual value, I get more and more accuracy.

Next, I turn the dial down to the `1000` setting, since this is still higher than the 220 Ω measured so far. When I read it this time, it says `218`. Since the setting does not have a `k` in the name, that means that this reading is 218 Ω. On my multimeter, the next setting is `200`, which is less than my last reading, so I will stop and say that my resistor is a 218 Ω resistor.

Note that you should *never test for resistance in a live circuit.* The multimeter uses power to measure resistance, and if there is already power in the circuit, it can damage the multimeter and/or the circuit.

6.5 Using a Multimeter with a Breadboard

We can use our multimeter with our breadboard, too. Let's say that we wanted to measure the voltage between the positive and negative rails of the breadboard. To do this, you would do the same procedure as you did with the battery, but, instead of connecting the leads of the multimeter directly to the battery terminals, you can shove the leads in the positive and negative rails of the breadboard.

To try this out, configure your breadboard similar to Figure 6.8. Use this layout, and *not* one of the ones with fewer wires (you will see why in a minute). With the battery connected to the breadboard, set your multimeter to the highest voltage setting, and put the red lead in any empty hole in the positive rail. While that lead is there, put the black lead in any empty hole in the negative rail.

This should give you the same reading that you received for the battery terminals. Remember that the power rails are connected all the way across—that is why putting your leads in any hole on the line works! If you work your way down the ranges on your multimeter, you should find that you get the same value that you did when you measured directly on the battery's leads.

You can now do the same to any component on your board. Let's find the voltage difference between one side of the resistor and the other. To do this, find an empty hole on the same terminal strip as the left-hand side of the resistor, and put the red lead from your multimeter in that hole. Then, find an empty hole on the same terminal strip as the right-hand side of the resistor, and put the black lead from your multimeter in that hole. Now you can measure the voltage difference. Note that to measure voltage differences, the circuit *must* be active. If the power is gone, the voltage difference will likely drop to zero. Use the same ranging procedure to find the voltage drop between the left-hand and right-hand side of the resistor.

Even though we have not discussed diodes, this doesn't prevent you from measuring the voltage difference between the legs of the diode in your circuit. Use the same procedure as before to measure the voltage drop.

6.6 Measuring Current with a Multimeter

Now we will learn to measure current using the same circuit layout from Figure 6.8. Like voltage, measuring current requires that the power to your circuit be on. To measure current, use the DC Amperage (sometimes called DC Current) settings on your multimeter.

Measuring current is a little different than measuring voltage in a circuit. Instead of just placing your leads in the breadboard as it is, you are going to use your leads to *replace a wire*. You will remove a wire, and then place your leads in the holes where the wire used to be. The circuit will then use your multimeter as that wire. The multimeter will then measure how much current was running through that wire, and report it to you on the screen. You will then need to use the same ranging technique as you used before with voltages and resistances to get an accurate report.

Let's say that you wanted to measure the current going through the wire that connects the resistor to the LED. To do this, we will start by *removing* that wire, and connecting the red lead to where the wire used to be on the left (since it is more positive), and the black lead to where the wire used to be on the right (since it is more negative). The multimeter should now report back how much current the circuit is using. This will vary for a number of reasons, but should be about 17 mA.

Now, put the wire back, and remove another wire and measure current there. No matter which wire you choose, they should all measure the same current. The reason is that, since all of these components are in series, they must all have the same amount of electricity flowing through them.

Review

In this chapter, we learned:

1. Solderless breadboards can be used to quickly create circuits.
2. Solderless breadboards allow circuits to be easily constructed and destructed in such a way that the components are reusable from one project to the next.
3. Both wire and the legs of a component are attached to connection points on the breadboard.
4. Connection points in the same terminal strip are connected by a wire behind the breadboard.
5. To connect two components together, all you have to do is put their legs on the same terminal strip of the breadboard.
6. The power rails on a breadboard extend all the way down the board. Power rails are connected all the way down the board.
7. The bridge of a breadboard divides and separates different groups of terminal strips. This allows a chip to be placed over the bridge, allowing each of its pins a separate terminal strip.
8. The schematic drawing of a circuit can be assembled onto a breadboard, giving a definite implementation of the drawing.
9. There are multiple different ways to place a given circuit drawing onto a breadboard.
10. Components on a breadboard can be connected by wires, or they can be connected by placing their legs in the same terminal strip.
11. There are many different styles of placing components onto breadboards, which have tradeoffs between how easy it is to reconfigure, and how clean the result is.
12. A multimeter allows you to measure several important values on a circuit, including resistance, voltage, and current.
13. If your multimeter is not auto-ranging, you must test your value several times, starting with the highest range setting for the value you are looking for, and decreasing it through the settings until you find a precise value.
14. Always be sure your multimeter is set to the right setting *before* measuring.
15. Always turn your circuit off before measuring resistance.
16. Your circuit must be on to measure voltage or current.
17. Voltage is measured by connecting your multimeter to empty connection points in the terminal strips that you want to measure.
18. Current is measured by using your multimeter to replace a wire that you want to measure current running through.
19. Many circuit values vary much more than what you might think, so it is good to design circuits in a way that will handle these variances.

Apply What You Have Learned

All measured values should be measured using the ranging technique discussed in this chapter.

1. Start with the circuit you built in Figure 6.8. Measure the voltage drop across the resistor, then measure the voltage drop across the LED. Now, measure the voltage drop across both of them (put the red multimeter lead on the left side of the resistor and the black multimeter lead on the right side of the LED). Write down your values.

2. Using the same circuit, change the LED from red to blue. Measure the values again and write them down. Measure the current going through the circuit using any wire. Is it the same or different than before?

3. Add another LED in series with the one you have already. Measure the voltage drops between each side of each component in the circuit. Measure the current going through any given wire. Write down each value.

4. Take the new circuit you built in the previous problem and draw the schematic for the circuit.

Chapter 7

Analyzing Series and Parallel Circuits

In the Chapter 5 we looked at our very first circuit and how to draw it using a circuit diagram. In this chapter, we are going to look at different ways components can be hooked together and what they mean for your circuit.

7.1 Series Circuits

The circuit built in Chapter 5 is considered a **series circuit** because all of the components are connected end-to-end, one after another. In a series circuit, there is only one pathway for the current to flow, making analyzing the circuit fairly simple.

It does not matter how *many* components are connected together—as long as all of the components are connected one after another, the circuit is considered a series circuit. Figure 7.1 shows a series circuit with several components included.

Figure 7.1: A Series Circuit with Several Components

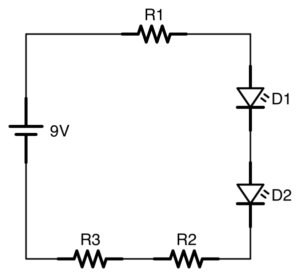
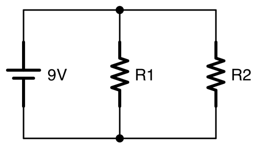


Figure 7.2: Two Resistors Wired in Parallel



If all of the components are in a series, then even if there are multiple resistors scattered throughout the circuit, you can figure out the total resistance of the circuit just by adding together all of the resistances. This is known as the **equivalent resistance** of the series.

In this example, if R1 is 100Ω, R2 is 350Ω, and R3 is 225Ω, then the total series resistance of the circuit will be $100 + 350 + 225 = 675\,\Omega$.

That means that the current is easy to figure out as well. If we ignore the LEDs (since we have not yet learned to calculate using them), then we can use the total series resistance to calculate current the same way we did with the single resistor.

Since the voltage is 9 volts, then we can use Ohm's law to find out the current going through the system.

$$I = V/R = 9/675 = 0.013\,\mathrm{A}$$

Note that A stands for ampere, and we will be using this in our calculations from here on out. However, in electronics, we usually measure in milliamps (abbreviated as mA), so let us convert:

$$0.013 * 1000 = 13\,\mathrm{mA}$$

So, our circuit will draw about 13 milliamps of current. This amount of current is the same amount running through all of the components in the series.

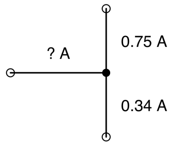
7.2 Parallel Circuits

Circuits are wired into a **parallel circuit** if one or more of their components are arranged into multiple branches.

Figure 7.2 shows a simple circuit with two resistors in parallel. In this figure, the circuit has *two* branches. R1 is in the first branch, and R2 is in the second branch. The place where the branch occurs is called a **junction**, and is usually marked with a dot to show that all the wires there are connected.

In a parallel circuit, electricity will flow through both branches simultaneously. Some of the current will go

Figure 7.3: A Simple Junction



through R1 and some of it will go through R2. This makes determining the total amount of current more difficult, as we have to take into account more than one branch.

However, there are two additional laws we can use to help us out, known as **Kirchoff's circuit laws**. The guy's name is hard to spell, but his rules are actually fairly easy to understand.

7.2.1 Kirchoff's Current Law

The first law is known as **Kirchoff's current law**. Kirchoff's current law states that, at any junction, the total amount of current going *into* a junction is exactly the same as the total amount of current going *out* of a junction. This should make sense to us. Think about traffic at a four-way intersection. The same number of cars that enter that intersection must be the same number of cars that leave the intersection. We can't create cars out of thin air, therefore each car leaving must have come in. Cars don't magically disappear, therefore each car entering must leave at some point. Therefore, Kirchoff's circuit law says that if you add up all of the traffic going in it will equal the amount going out.

— **Advanced: Another Way of Looking at It**

Another way to say this is that the total amount of all of the currents at a junction is zero. That is, if we consider currents coming in to the junction to be positive and currents going out of the junction to be negative, then their total will be zero since the size of the currents coming in must equal the size of the currents going out.

So, let's look at a junction. Figure 7.3 shows a junction where one wire is bringing current in, and it branches with two wires bringing current out. The first wire going out has 0.75 A of current, and the second wire going out has 0.34 A of current. How much current is going into the junction from the left?

Since the total coming in must equal the total coming out, then that means the total coming in must be

$$0.75\,\mathrm{A} + 0.34\,\mathrm{A} = 1.09\,\mathrm{A}$$

Therefore, the total amount of current coming into the circuit is 1.09 A.

Figure 7.4: A Circuit With Many Parallel Paths

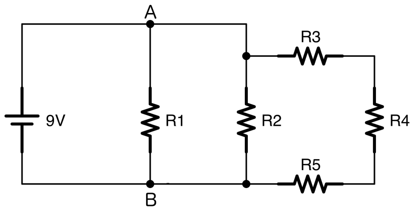
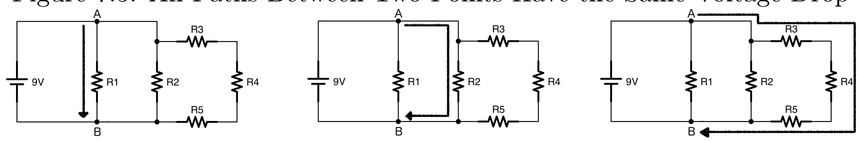


Figure 7.5: All Paths Between Two Points Have the Same Voltage Drop



Now, lets say we had a junction of four wires. In the first wire, we have 0.23 A of current coming in. On the second wire, we have 0.15 A of current going out. On the third wire, we have 0.20 ampere of current going out. What must be happening on the fourth wire? Is current coming in or going out on that wire?

To figure that out, we have to look at the totals so far. Coming in, we have the one wire at 0.23 A. Going out, we have the two wires for a total of 0.15 A + 0.20 A = 0.35 A. Since we only have 0.23 A coming in, but there is 0.35 A going out, that means that the fourth wire must be bringing current in. Therefore, the amount that this fourth wire must be bringing in is 0.35 A – 0.23 A = 0.12 A.

7.2.2 Kirchoff's Voltage Law

Kirchoff's current law makes a lot of sense, because the amount of "stuff" coming in is the same as the amount of "stuff" going out. This is similar to our everyday experience. Kirchoff's voltage law, however, is a bit more tricky. **Kirchoff's voltage law** states that, given any two points on a circuit at a particular time, that no matter what path is travelled to get between those two points, the difference in voltage between the two points (known as the **voltage drop**) is the same *no matter what pathway you take to get there.*

Figures 7.4 and 7.5 illustrates this point. If we wanted to measure the voltage drop between the two points indicated (A and B), then that voltage drop, at least at a particular point in time, will be the same no matter what pathway electricity travels. The direct route between the two points has the same voltage drop as the more winding pathways, no matter what the values of the resistors are.

So how does that square with Ohm's law?

The way it works is that Ohm's law will cause all of the *currents* through each part of the circuit to adjust in order to make sure that the *voltage* stays the same.

As you can see, the voltage drop between A and B *must* be 9 volts because the battery is a 9-volt battery, and there are no components (only wires) between the battery terminals and A and B. Since batteries always have a constant voltage between their terminals, that means that A and B will have the same voltage—9 volts.

Therefore, that means that the voltage drop across R1 is 9 volts, because it is one of the pathways between A and B, and all pathways get the same voltage. Let's put in some real values for these resistors and see if we can figure out how much voltage and current is happening in each part of the circuit. Let's set R1 = $1,000\,\Omega$, R2 = $500\,\Omega$, R3 = $300\,\Omega$, R4 = $400\,\Omega$, and R5 = $800\,\Omega$. Now, let's find out what our circuit looks like.

As we have noted, *every* path must have the same voltage drop—9 volts. So let's start with the easiest one, the current going across R1. Since we have a 9-volt drop and $1,000\,\Omega$, we can just use Ohm's law for current:

$$I = V/R = 9\,\mathrm{V}/1,000\,\Omega = 0.009 \text{ A}$$

So, we have 0.009 A running across R1.

Now, what about R2? R2 is connected to point A simply by a wire. As we mentioned in Section 5.4, wires can be considered to be zero-length. Therefore, R2 is just as much directly connected to point A as R1 is. Therefore, the voltage drop across R2 is also going to be 9-volts. Again, using Ohm's law, we can see that

$$I = V/R = 9\,\mathrm{V}/500\,\Omega = 0.018 \text{ A}$$

So, the current going across R2 is 0.018 A.

What about the current going across R3, R4, and R5? Well, if you notice, those resistors are all in series, so we can add them all up and just use the total resistance.

So, the total resistance for this section of the circuit will be:

$$R3 + R4 + R5 = 300\,\Omega + 400\,\Omega + 800\,\Omega = 1,500\,\Omega$$

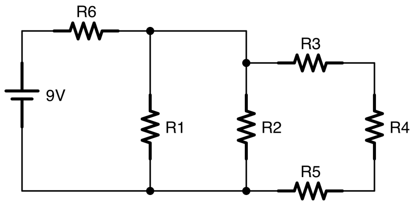
So, using Ohm's law, the current running through this part of the circuit will be:

$$I = V/R = 9\,\mathrm{V}/1,500\,\Omega = 0.006 \text{ A}$$

Now, remember that the total current flowing into any junction has to be equal to the current flowing out of it. So, let's look at the junction between R2 and R3. We calculated that the current flowing to R2 is 0.018 A and the current flowing to the series starting with R3 is 0.006 A. Therefore, there has to be $0.018 + 0.006 = 0.024$ A flowing into that junction.

Now, how much current is flowing out of junction A? Well, earlier, we noted that the amount of current flowing across R1 was 0.009 A, and we just calculated that there is 0.024 A flowing out of A into the junction between R2 and R3. That means that there must be 0.033 A total flowing into junction A.

Figure 7.6: Kirchoff's Voltage Law with Series and Parallel Components



While there were a lot of steps to determine this, each individual step was fairly straightforward. We simply combined Ohm's law, Kirchoff's voltage law, and Kirchoff's current law to figure out each step.

Now, one important thing to notice is that there is *less* current running through the pieces of the circuit with more resistance than there is with the pieces of the circuit with less resistance. The electric current is more likely to go down the path of least resistance. This is a very important point and should not be overlooked, as it will come in handy in later chapters.

7.3 Equivalent Parallel Resistance

The sort of calculation that we have done in the previous section gets trickier if there is a series resistance before or after the parallel resistance. Figure 7.6 gives an example of this. The setup is just like the previous circuit, except there is a single resistor (R6) in series with the battery *before* the parallel branches. This will prevent our simple calculations from working because the current flowing in each of the branches of the circuit will all add together to tell us the amount of current flowing through R6. However, the voltage drop across R6 will depend on the current flowing through it. If this voltage changes, then it will change our starting voltage for our calculations to figure out the parallel branches.

Thus, we have ourselves in a loop—in order to find out the current flowing through the parallel branches, we have to know their starting voltage. In order to find out their starting voltage, we have to know how much the voltage dropped across R6. In order to know how much the voltage dropped across R6, we have to know how much current was flowing through it!

This may seem like an impossible problem, but basic algebra allows us to work it out, though the details are kind of ugly. Instead, we have an equation which gives us **equivalent resistance**. That is, we can take a series of parallel resistors, and we can calculate the total resistance of those resistors.

If you have resistors in parallel to each other (let's call them R_1, R_2, and R_3), and you want to know the resistance of their *combined* action (which we will call this total R_T), then you would use the following equation:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \tag{7.1}$$

This equation works for any number of resistances that we have in parallel. We can just keep on adding them to the end of the list:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_N}} \tag{7.2}$$

So, let's look at our circuit, and see how we can find out the currents flowing through each resistor. For this example, we will again say that $R1 = 1,000\,\Omega$, $R2 = 500\,\Omega$, $R3 = 300\,\Omega$, $R4 = 400\,\Omega$, and $R5 = 800\,\Omega$. Additionally, $R6 = 250\,\Omega$.

In order to compute this, we first have to figure out *what* is in series and what is in parallel. Notice the loop made by R3, R4, and R5. Those are all connected end-to-end, so they are in series. Because they are in series, we can get their equivalent resistance just by adding them together—$300 + 400 + 800 = 1,500\,\Omega$. Therefore, we can actually *replace* these resistors with a single, $1,500\,\Omega$ resistor. We will call this "combined" resistor R7. Now, if you look at the new picture, with R7 standing in for the loop, you will see that R1, R2, and R7 are in parallel with each other.

Therefore, we can find out their combined resistance by using Equation 7.2:

$$\begin{aligned}
R_T &= \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R7}} \\
R_T &= \frac{1}{\frac{1}{1{,}000} + \frac{1}{500} + \frac{1}{1{,}500}} \\
R_T &= \frac{1}{0.001 + 0.002 + 0.00067} \\
R_T &= \frac{1}{0.00367} \\
R_T &= 272.5\,\Omega
\end{aligned}$$

Therefore, the equivalent resistance of all of the parallel resistances is about $272.5\,\Omega$, which means that we can replace *all* of these resistors (R1, R2, R3, R4, and R5) with a single resistor that is $272.5\,\Omega$. Also notice that this resistance is actually *less* than each of the individual resistances.

Now, to get the total resistance of the circuit, we notice that this parallel resistance ($272.5\,\Omega$) is in series with R6, which is $250\,\Omega$. Since they are in series with each other, we can simply add them together. The total resistance of this circuit is $250 + 272.5 = 522.5\,\Omega$. We can now use Ohm's law to find the total amount of current running through this circuit:

$$\begin{aligned}
I &= \frac{V}{R} \\
I &= \frac{9}{522.5} \\
I &= 0.0172\,\mathrm{A}
\end{aligned}$$

Thus, the whole circuit has 0.0172 amperes of current running through it. Using this, we can now go back through and identify how much current and voltage is flowing through each individual piece.

Because the entirety of the 0.0172 amperes is going through the first resistor, that means that the voltage drop of this resistor will be, using Ohm's law:

$$
\begin{aligned}
V &= I \cdot R \\
V &= 0.0172 \cdot 250 \\
V &= 4.3\,\mathrm{V}
\end{aligned}
$$

That means that this resistor will chew up 4.3 V. This leaves us with $9 - 4.3 = 4.7\,\mathrm{V}$ left after the series resistor.

We now know the starting and ending voltages of each branch of the parallel resistors—4.7 V at the beginning (what we just calculated the voltage to be after the series resistor), and 0 V at the end (because it connects to the negative terminal of the battery, which we have designated as the zero volt reference).

Therefore, we can use Ohm's law to find the amount of current flowing through each of them. For R1:

$$
\begin{aligned}
I &= \frac{V}{R} \\
I &= \frac{4.7}{1,000} \\
I &= 0.0047\,\mathrm{A}
\end{aligned}
$$

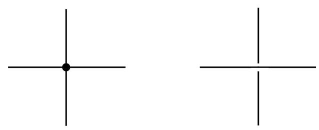
For R2:

$$
\begin{aligned}
I &= \frac{V}{R} \\
I &= \frac{4.7}{500} \\
I &= 0.0094\,\mathrm{A}
\end{aligned}
$$

And finally, for the series that is in a loop at the right (R3, R4, and R5):

$$
\begin{aligned}
I &= \frac{V}{R} \\
I &= \frac{4.7}{1500} \\
I &= 0.0031\,\mathrm{A}
\end{aligned}
$$

Figure 7.7: Joined Wires (left) vs. Unjoined Wires (right)



Since the loop is all in series, that means all of the resistors in that series will have 0.0031 A going through them.

If we add all of these currents, we will see that $0.0031 + 0.0094 + 0.0047 = 0.0172$ A, which is the amount of current we originally figured out.

What we have learned is that we can replace the entire circuit with a single value for its resistance to figure out how the circuit will behave as a whole. For a simple circuit like this, having all of these parallel branches doesn't do much, so it may seem pointless. However, in a real circuit, each of these branches may be, instead of a resistor, a component that has some amount of resistance. If you know the resistance, you can calculate how much current is flowing through it the same way.

However, we start with only resistors in order to make the problems simpler.

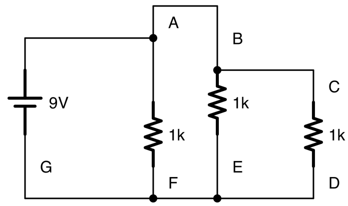
7.4 Wires in a Circuit

In complicated circuits, sometimes we run out of room and must draw wires on top of each other even though the wires aren't connected. In this book, we try to make clear which wires are connected by placing a dot on the junction point. To show two wires that don't connect to each other, but which had to cross because the diagram was too complicated to prevent it, we will show one of the wires as being broken across the intersection point. Figure 7.7 demonstrates the difference. The wires on the left are joined together as indicated by the dot. The wires on the right are not joined in any way, they just had to be drawn across each other because of space reasons in the diagram.

Also, the lengths of wires that we draw are irrelevant. Usually, in simple circuits, we should consider that wires are all zero-length. If, after a resistor, the voltage in the circuit has dropped to 5 V, then we can consider that the *whole wire* until the next circuit is at 5 V. If a wire branches into multiple branches, even though each branch will have a different amount of *current* running on the branch, each branch of the wire will all have the *exact same voltage* until they reach another component.

Therefore, in the circuit in Figure 7.8, you can see several points labelled A, B, C, D, E, F, and G. In this circuit, A, B, and C all have equivalent voltages (though not equivalent currents) since there are only wires (and not components) between them. Likewise, D, E, F, and G all have equivalent voltages since there are only wires between them. Also, since D, E, F, and G are all connected to the battery negative (i.e., ground) with no components between them, that means that they are all at zero volts. Likewise, since A, B, and C are all directly connected to the battery positive with no intervening components, they are all at 9 volts.

Figure 7.8: Several Points on a Circuit



Review

In this chapter, we learned:

1. In a series circuit, electricity flows in a single line through all of the components.
2. In a parallel circuit, electricity branches and flows in multiple branches.
3. Most real circuits are combinations of series and parallel circuits.
4. When you have resistors together in series, the total resistance of all of the resistors combined is simply the sum of their individual resistances.
5. In a parallel circuit, Kirchoff's Current Law says that the total amount of current entering a branch/junction is the same as the total amount of current leaving the branch.
6. In a parallel circuit, Kirchoff's Voltage Law says that, between any two points on a circuit at a given point in time, the voltage difference between those two points will be identical no matter what pathway the electricity follows to get there.
7. When resistances are in parallel, the total resistance for the parallel circuit is given by the equation $R_T = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\ldots+\frac{1}{R_N}}$.
8. By using these laws in combination, we can predict how current will flow in each part of our circuit.

Apply What You Have Learned

1. There is a junction in a circuit that has one wire with current flowing in and two wires with current flowing out. There is 1.25 A of current coming in, and the first wire going out has 0.15 A of current going out. How much current is leaving through the second wire?
2. There is a junction in a circuit that has two wires with current flowing in and two wires with current flowing out. The first wire with current flowing in has 0.35 A of current, the first wire with current flowing out has 0.25 A of current, and the second wire with current flowing out has 0.42 A of current. How much current is flowing in on the second incoming wire?

3. At a junction of four wires, wire 1 has 0.1 A of current flowing in, wire 2 has 0.2 A of current flowing in, and wire 3 has 0.4 A of current flowing out. Is the current in wire 4 going in or out? How much current is flowing on it?

4. If I have three $100\,\Omega$ resistors in series, what is the total resistance of the series?

5. If I have a $10\,\Omega$ resistor, a $30\,\Omega$ resistor, and a $65\,\Omega$ resistor in series, what is the total resistance of the series?

6. If I have a $5\,\Omega$ resistor and a $7\,\Omega$ resistor in series, what is the total resistance of the series?

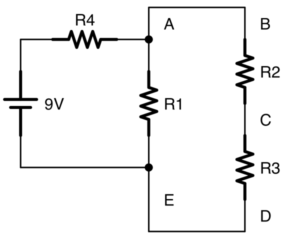
7. If I have two resistors in parallel, a $30\,\Omega$ resistor and a $40\,\Omega$ resistor, what is the total resistance of this circuit?

8. If I have three resistors in parallel—$25\,\Omega$, $40\,\Omega$, and $75\,\Omega$, what is the total resistance of this circuit?

9. If I have four resistors in parallel—$1,000\,\Omega$, $800\,\Omega$, $2,000\,\Omega$, and $5,000\,\Omega$, what is the total resistance of this circuit?

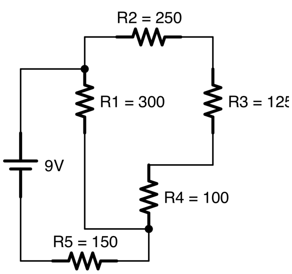
10. If I have three resistors in parallel—$100\,\Omega$, $5,000\,\Omega$, and $10,000\,\Omega$—what is the total resistance of this circuit? Which of the resistors is the total resistance most similar to?

11. Take a look at the following circuit diagram. If the voltage drop between B and C is 2 volts, and the voltage drop between C and D is 3 volts, what is the voltage drop between A and E? What is the voltage at E? What is the voltage at A?



12. Optional - what resistor values would you need to have the circuit above run with 2 A total current?

13. The circuit below is a combination of series and parallel resistances. Each resistor is labelled with its resistance value, given in ohms. Find out how much current is flowing through each resistor, and how much each resistor drops the voltage.



Appendix A

Glossary

AC current See *alternating current.*

AC mains current This is the type of current that is supplied to your house by the public utility companies. This is usually 120 volts AC and cycles back and forth 50–60 times per second.

AC signal current This is the type of current usually picked up by a microphone or antenna. It has very low current and usually must be amplified before processing.

alternating current

amp A shorthand way of saying ampere. See *ampere.*

ampere An ampere is a measurement of the movement of charge. It is equivalent to one coulomb of charge per second moving past a given point in a circuit.

charge Charge is a fundamental quantity in physics. A particle can be positively charged (like a proton), negatively charged (like an electron), or neutrally charged (like a neutron). Charge is measured in coulombs.

closed circuit A circuit is closed if there is a complete pathway from the positive to the negative.

conventional current flow

coulomb A coulomb is a quantity of electric charge. One coulomb is roughly equivalent to the charge of 6.242Ö10^{1}8 protons. The same number of electrons produces a charge of -1 coulomb. Coulombs are represented by the symbol C.

DC current See *direct current.*

direct current

electron current flow

electron A negatively-charged particle that is usually on the outside of an atom.

milliamp A short way of saying milliampere. See *milliampere*.

milliampere One thousandth of an ampere. See *ampere*.

neutron An uncharged particle in the nucleus of an atom.

nucleus The nucleus is the part of the atom where protons and neutrons reside.

open circuit An open circuit is a condition where there is no electrical pathway for the current to flow. See also *closed circuit*, *short circuit*.

parallel circuit A circuit is a parallel circuit if one or more components are arranged into multiple branches.

proton A positively-charged particle in the nucleus of an atom.

resistance Resistance measures how much a component resists the flow of electricity. Resistance is measured in ohms (Ω).

series circuit A series circuit is a circuit or part of a circuit where all of the components are connected one after another.

short circuit A short circuit is what happens when the current pathway has no resistance from the positive to the negative.

Appendix B

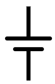
Finding Component Values

Since electronic components are so small and oddly-shaped, manufacturers have had to come up with some strange systems to let you know what values your components hold. This appendix will tell you how, in most cases, to tell the values of different components.

B.1 Resistors

Appendix C

Electronics Symbols

Symbol	Component	Description
	Battery	A battery is represented by a long line and a short line stacked on top of each other. Sometimes, there are two sets of long and short lines. The long line is the positive terminal and the short line is the negative terminal (which is usually used as the ground).
	Resistor	A resistor is represented by a sharp, wavy line with wires coming out of each side.
	LED	An LED is represented by an arrow with a line across it, indicating that current can flow from positive to negative in the direction of the arrow, but it is blocked going the other way. The LED symbol also has two short lines coming out of it, representing the fact that it emits light.

Appendix D

Electronics Equations