
ELECTRONICS FOR EVERYBODY

Electronics for Everybody

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ELECTRONICS FOR EVERYBODY

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—Author

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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 0.000003333333, 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 the electric charge of 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 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 **ampères**, 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 millamps, and abbreviated as mA. The prefix *milli-* means one thousandth of (i.e., $\frac{1}{1000}$ or 0.001). Therefore, a millamp is one thousandth of an amp. If someone says that there is 20 millamps 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 millamps.

So, to go from amps to millamps, multiply the value by 1,000. To go from millamps 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 millamps is that? To go from amps to millamps, we multiply by 1,000. $2.3 * 1,000 = 2,300$. Therefore, 2.3 amps is the same as 2,300 millamps.

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 millamps of current flowing, how many amps of current do I have flowing?
2. If I have 1,450 millamps 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 0.0000001 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:

$$V = I * R \quad (4.1)$$

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 that comes out of the faucet 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:

$$I = V/R \quad (4.2)$$

$$R = V/I \quad (4.3)$$

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, GND, 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 millamps). 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

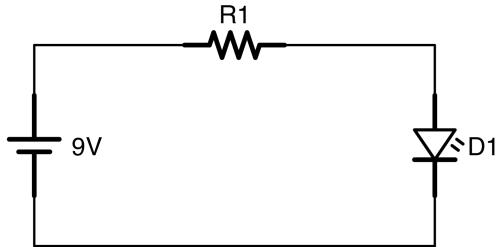
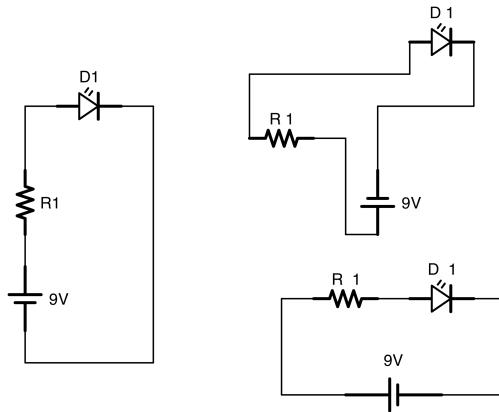


Figure 5.4: Alternative Ways of Drawing the Basic LED Circuit



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

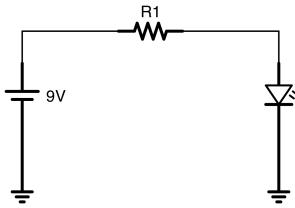
Notice that each of our components are laid out on the diagram with wires connecting them. Remember that it doesn't matter if we have very long wires, very short wires, or if the components are directly placed end-to-end—the resulting circuits will operate identically. Also notice that each component 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 is 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).

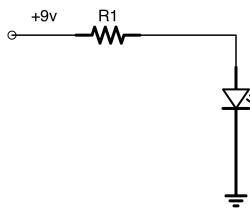
Therefore, the circuit in Figure 5.5 is the same circuit as before, just drawn using the ground symbol. Since every point with the ground symbol are all connected together, using this symbol on both the negative terminal and the negative side of the LED means that they are wired together.

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 millamps.
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 permanently.

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

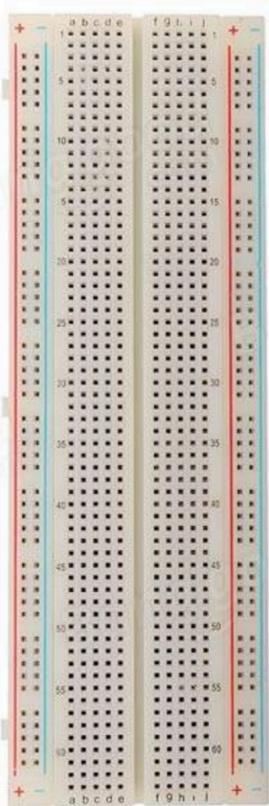
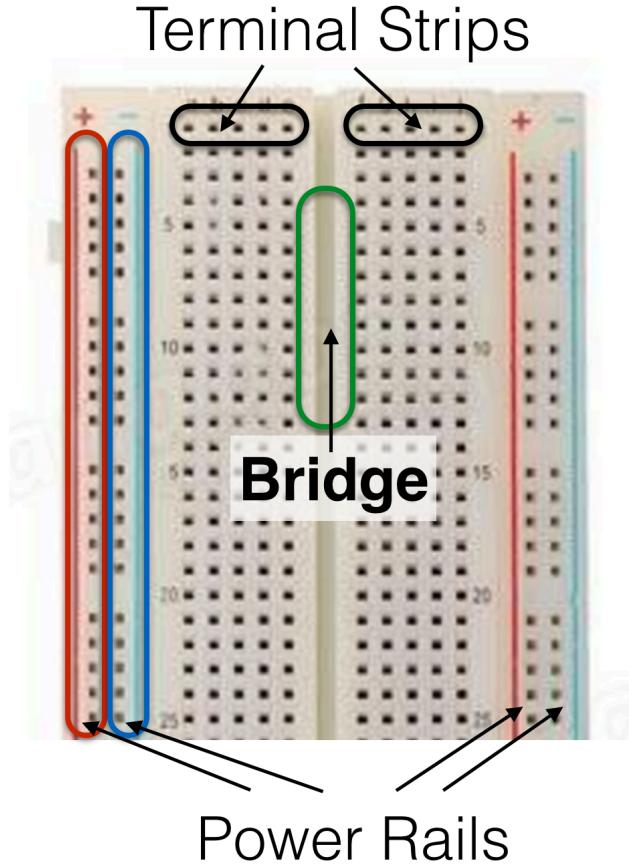


Figure 6.2: Parts of a Solderless Breadboard



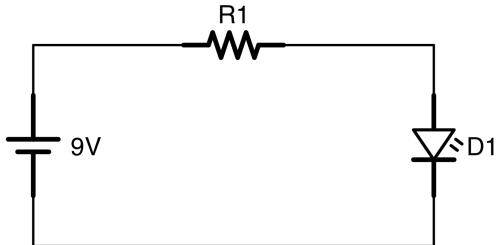
terminal strip are themselves connected.

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, many more of the connection points are connected together, even when there are short gaps. Some boards will split the power rails at the halfway point, but others go all the way down the board. This is usually visually indicated by a break in the red and blue lines that indicate the power rails.

Figure 6.3: Basic LED Circuit



Note that 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 breadboard (unless you connect them manually). As we mentioned, on some breadboards, even a single side isn't connected all the way down, but may be broken into sections at the halfway point.

In many projects, many components need direct access to the positive or negative power supply. Power rails make this easy by providing a connection point with positive and negative power a very short distance away from wherever you need it on the breadboard. 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 appropriate 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.

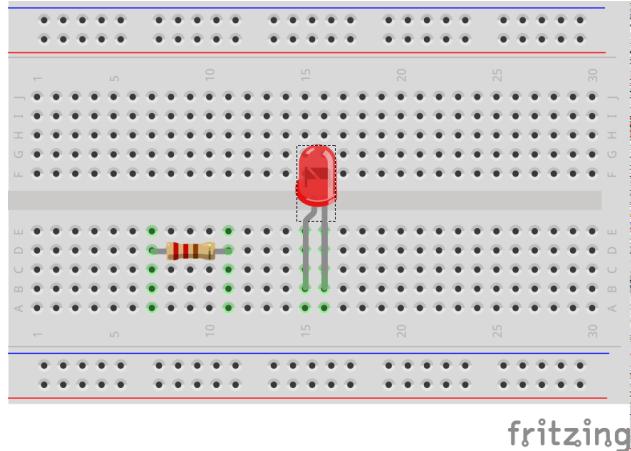
So, how do we translate what we see in the drawing to what we need to put in the breadboard? Well, let's take a look at what is in the circuit—a 9-volt battery, an LED, and a resistor. Let us not concern ourselves with the battery at the moment. So, without the battery, we have a resistor connected to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

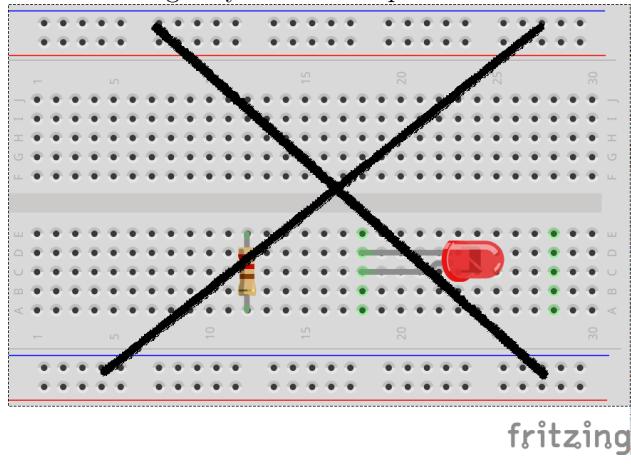
Now, to connect the resistor to the LED, we need to add a wire. So, all we need to do is connect a wire to

Figure 6.4: Putting the Components onto the Breadboard



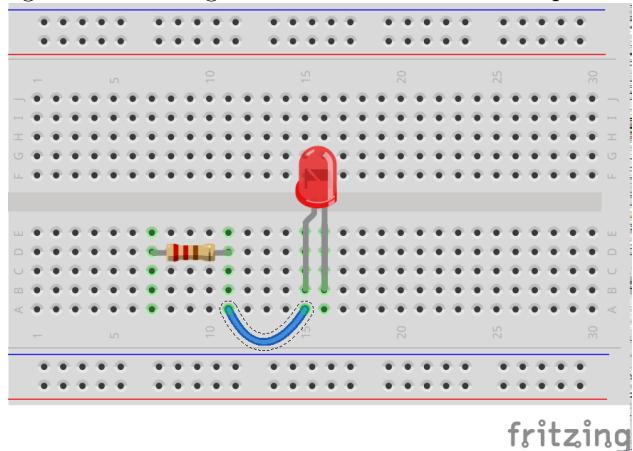
fritzing

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



fritzing

Figure 6.6: Adding a Wire to Connect the Components



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.

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

Figure 6.7: Adding Wires to the Power Rails

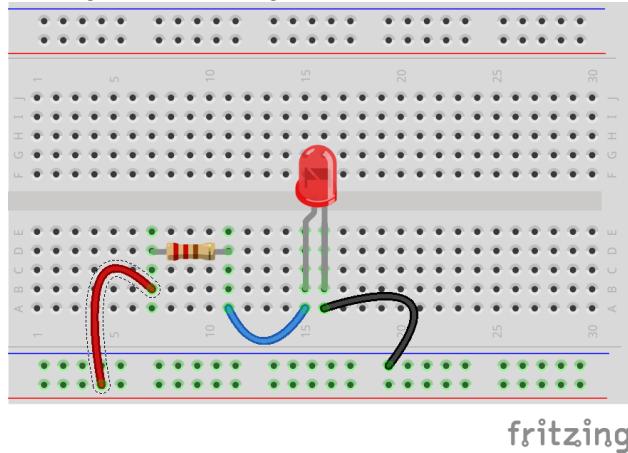


Figure 6.8: Final LED Circuit with Power Connected

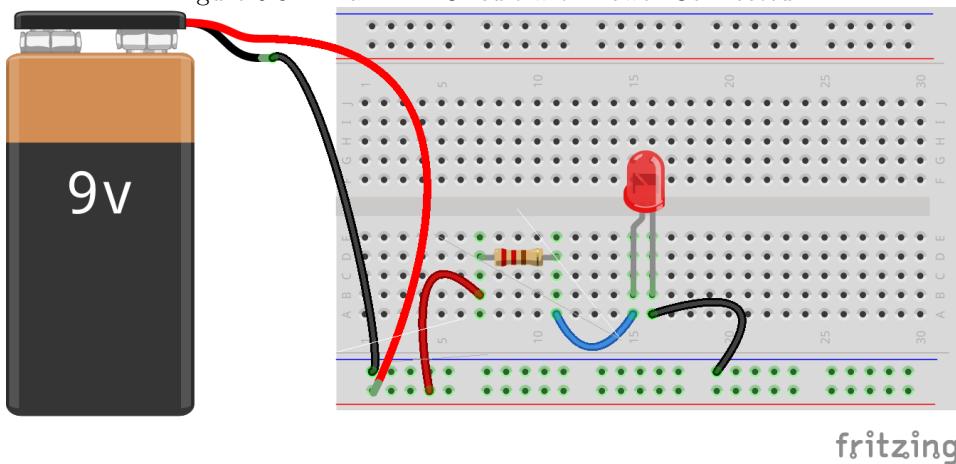
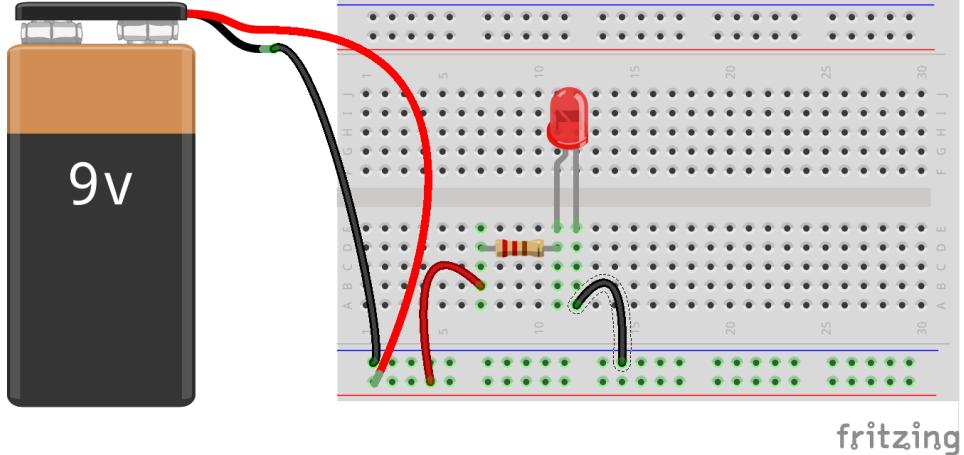


Figure 6.9: Joining Components by Putting Their Leads on the Same Terminal Strip



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!*
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.

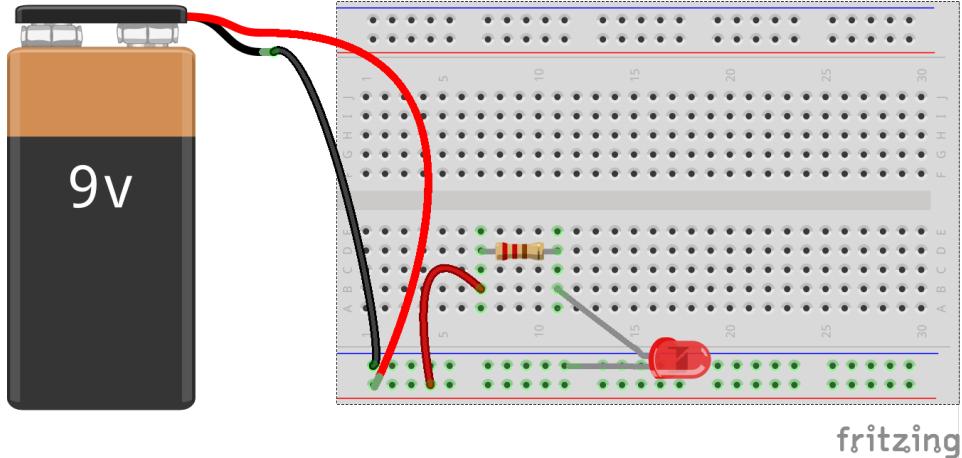
6.3 Using Fewer Wires

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.

Figure 6.10: Directly Connecting the LED to the Negative Rail



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.

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.

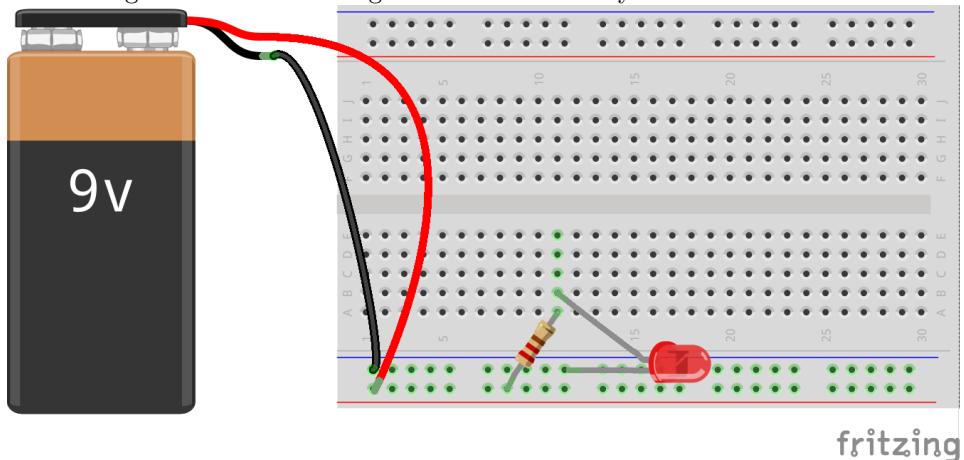
Therefore, as you can see, there are any number of ways that you can arrange parts on a breadboard to match a given schematic. All of these arrangements we have seen match the schematic given in Figure 6.3. As long as your circuit matches the configuration in the schematic, the specifics of where you 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 *multiple* different things about a circuit.

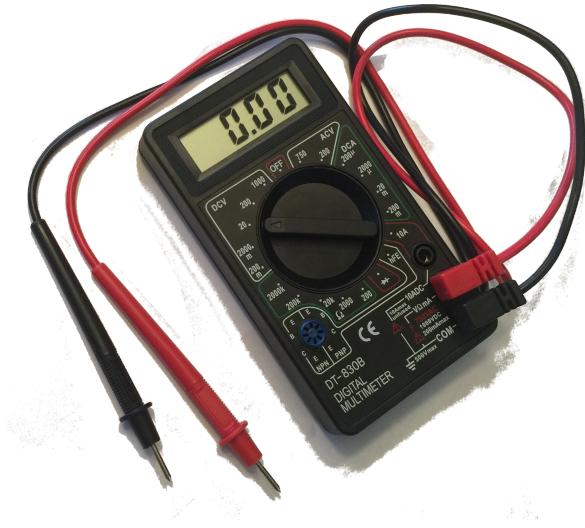
There are a lot of different multimeters around which have a lot of different functions. However, almost all of them will measure voltage, current, and resistance. Each of these values are measured by testing two different points on the circuit. Most multimeters have a red lead and a black lead. The 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 then 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 $0.2\text{k}\Omega$, or around 200Ω . 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 220Ω . 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 220Ω 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 218Ω . 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 218Ω 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.

There are two ways to do this. The first, if the size of your multimeter probes and the size of your breadboard connection points allow it, is to simply shove the leads of your multimeter into connection points on the positive and negative rails. Since these will be connected to the power by a wire, these will be at the same voltage levels as the battery itself.

However, if your breadboard/multimeter combination does not support this, you can do the same thing by simply connecting two jumper wires into the positive and negative rails, and then testing the voltage on the other end of the wires.

Also, if you are testing components for voltage, you can also use your multimeter on the exposed legs of the component. This is often easier than either trying to push your leads into the breadboard or running extra wires to your multimeter.

To try out using your multimeter with your breadboard, 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. Again, if your leads do not fit inside the connection points, you can also use wires to connect out from your breadboard to your multimeter 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 (connection points) where the wire used to be. Alternatively, if your multimeter does not fit into the connection points, you can again run two wires, one from each hole, from the breadboard to your multimeter leads.

Using either of these approaches, the circuit will then use your multimeter as the wire that was removed, and the multimeter will then measure how much current is 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 (one right after the other), they must all have the same amount of electricity flowing through them (otherwise, where would the electricity be going?).

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 deconstructed 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 either all the way down the board, or sometimes split at the halfway point.
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. This can be done either by putting your multimeter leads directly into the relevant connection points or by running wires from those connection points to your multimeter leads.
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

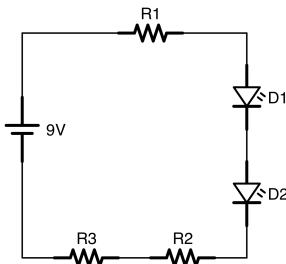
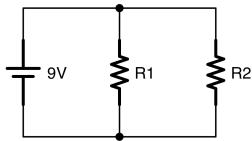


Figure 7.2: Two Resistors Wired in Parallel



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 R_1 is 100Ω , R_2 is 350Ω , and R_3 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.

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

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 millamps (abbreviated as mA), so let us convert:

$$0.013 * 1000 = 13 \text{ mA}$$

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

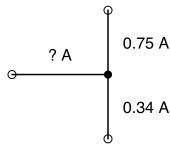
7.2 Parallel Circuits

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. R_1 is in the first branch, and R_2 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

$$0.75 \text{ A} + 0.34 \text{ A} = 1.09 \text{ A}$$

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

Figure 7.4: A Circuit With Many Parallel Paths

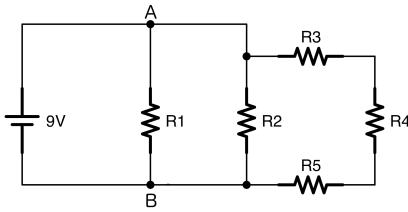
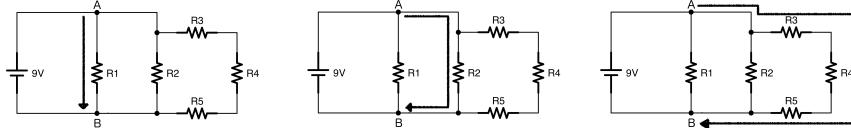


Figure 7.5: All Paths Between Two Points Have the Same Voltage Drop



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 $0.15\text{ A} + 0.20\text{ A} = 0.35\text{ A}$. 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 $0.35\text{ A} - 0.23\text{ A} = 0.12\text{ A}$.

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 $R_1 = 1,000\Omega$, $R_2 = 500\Omega$, $R_3 = 300\Omega$, $R_4 = 400\Omega$, and $R_5 = 800\Omega$. 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:

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

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

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

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:

$$R_3 + R_4 + R_5 = 300\Omega + 400\Omega + 800\Omega = 1,500\Omega$$

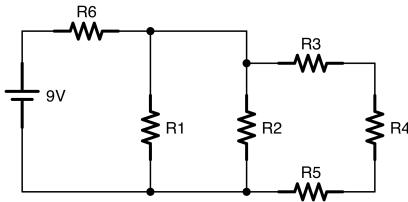
So, using Ohm's law, the current running through this part of the circuit will be:

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

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 (R_6) 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 R_6 . However, the voltage drop across R_6 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 R_6 . In order to know how much the voltage dropped across R_6 , 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 group of parallel resistors, and we can calculate the total resistance of those resistors. In other words, we can find out what value we would need for a single resistor to replace all of the other resistances.

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:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \quad (7.1)$$

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:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_N}} \quad (7.2)$$

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:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_7}} \\ R_T &= \frac{1}{\frac{1}{1,000} + \frac{1}{500} + \frac{1}{1,500}} \\ R_T &= \frac{1}{0.001 + 0.002 + 0.00067} \\ R_T &= \frac{1}{0.00367} \\ R_T &= 272.5 \Omega \end{aligned}$$

Therefore, the equivalent resistance of all of the parallel resistances is about 272.5Ω , which means that we can replace *all* of these resistors (R1, R2, R3, R4, and R5) with a single resistor that is 272.5Ω . 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 (272.5Ω) is in series with R6, which is 250Ω . 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:

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

$$I = \frac{9}{522.5}$$

$$I = 0.0172 \text{ A}$$

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:

$$V = I \cdot R$$

$$V = 0.0172 \cdot 250$$

$$V = 4.3 \text{ V}$$

That means that this resistor will chew up 4.3 V. This leaves us with $9 - 4.3 = 4.7 \text{ V}$ 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:

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

$$I = \frac{4.7}{1,000}$$

$$I = 0.0047 \text{ A}$$

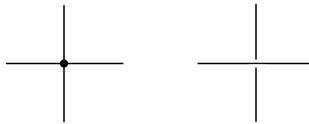
For R2:

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

$$I = \frac{4.7}{500}$$

$$I = 0.0094 \text{ A}$$

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



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

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

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 $0.0031 + 0.0094 + 0.0047 = 0.0172 \text{ A}$, 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

Figure 7.8: Several Points on a Circuit

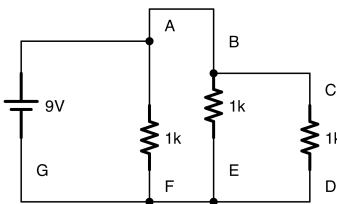
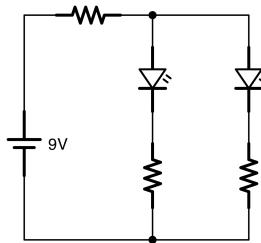


Figure 7.9: A Circuit with Series and Parallel Components



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.

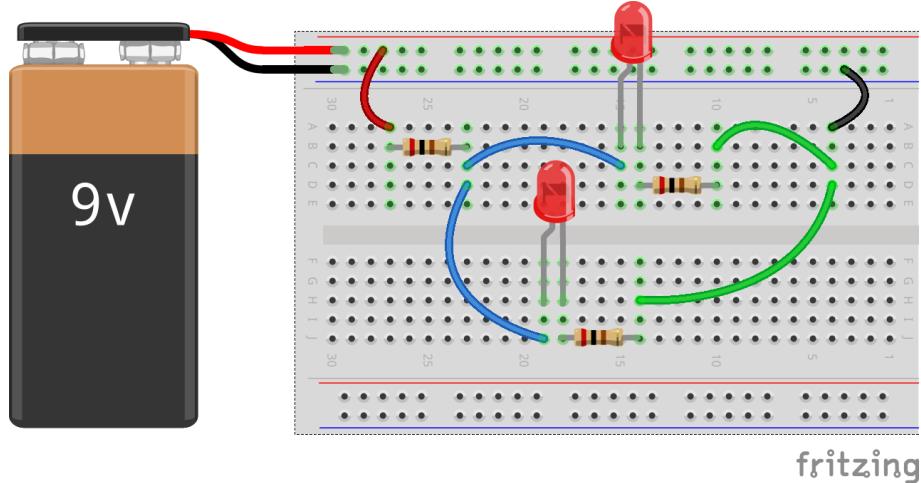
Therefore, in the circuit in Figure 7.8, you can see several points labelled A, B, C, D, E, F, and G. In this circuit, A, B, and C all have equivalent voltages (though not equivalent currents) since there are only wires (and not components) between them. Likewise, D, E, F, and G all have equivalent voltages 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.

7.5 Wiring Parallel Circuits Onto a Breadboard

One other issue we need to look at is how to wire parallel circuits onto the breadboard. It is actually very simple to do. In this section, we are going to put the circuit in Figure 7.9 onto a breadboard.

Notice that, in this circuit, there is a series resistor at the beginning, and then two parallel circuits that branch off from it. It doesn't matter much what the value of the resistors are, but we will put them at 200Ω if you need a specific value (anything between 200 and $1,000\Omega$ should work fine).

Figure 7.10: A Circuit with Series and Parallel Components on the breadboard



To get the circuit onto the breadboard, remember that anything that is connected in the same terminal strip on a breadboard is connected together. This means that, when we have a parallel subcircuit, we connect all of the branches of the subcircuit into the same terminal strip. Figure 7.10 shows what this looks like.

Let's follow the path of electricity through the breadboard. First, the current flows from the positive terminal to the positive rail on the breadboard. A wire then pulls the positive +9 V power onto the board. This wire is connected to a resistor by putting one leg of the resistor in the same terminal strip as the wire. On the other leg of the resistor there are *two* wires that are in the same terminal strip. Each of these go to a different part of the circuit. We have one LED with a resistor on the top, and one LED with a resistor on the bottom. These are just normally connected components.

However, after the resistor, the two subcircuits come back together to a terminal strip on the right. Then, a wire on the same terminal strip takes that back to the negative rail on the breadboard (which connects to the negative terminal on the battery).

Note that, in this case, I could have just connected the two subcircuits directly back to the negative, but I thought having them come together on a terminal strip would illustrate more clearly the general method of bringing circuits back together.

Take a moment to look at both the schematic drawing and the breadboard picture, and be sure that you can trace the flow of the schematic on the actual breadboard.

Review

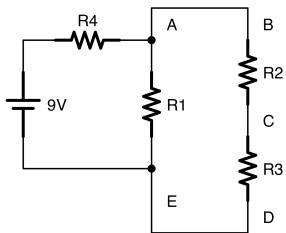
In this chapter, we learned:

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
$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_N}}.$$
8. By using these laws in combination, we can predict how current will flow in each part of our circuit.
9. Series circuits are placed onto a breadboard by putting the connected legs of two connected components onto the same terminal strip.
10. Parallel circuits are placed onto a breadboard by connecting each subcircuit branch to the same terminal strip.

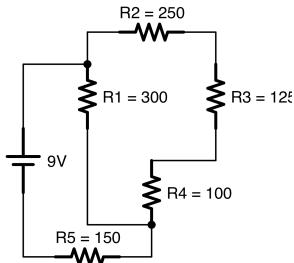
Apply What You Have Learned

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 100Ω resistors in series, what is the total resistance of the series?

5. If I have a 10Ω resistor, a 30Ω resistor, and a 65Ω resistor in series, what is the total resistance of the series?
6. If I have a 5Ω resistor and a 7Ω resistor in series, what is the total resistance of the series?
7. If I have two resistors in parallel, a 30Ω resistor and a 40Ω resistor, what is the total resistance of this circuit?
8. If I have three resistors in parallel— 25Ω , 40Ω , and 75Ω , what is the total resistance of this circuit?
9. If I have four resistors in parallel— $1,000\Omega$, 800Ω , $2,000\Omega$, and $5,000\Omega$, what is the total resistance of this circuit?
10. If I have three resistors in parallel— 100Ω , $5,000\Omega$, 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.



14. Build the circuit in Figure 7.10 on your own breadboard. Measure the voltage drops across every component, and measure the amount of current flowing into the first series resistor.

Chapter 8

Diodes and How to Use Them

This chapter introduces the **diode**. We have used light-emitting diodes (LEDs) in previous chapters, but have not really discussed their function except for emitting light. In this chapter, we are going to look at regular diodes, light-emitting diodes, and Zener diodes, to get a feel for what these devices are and how they might be used in circuits for more than just light.

8.1 Basic Diode Behavior

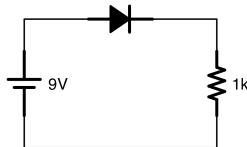
Unlike resistors, diodes have both a positive and negative side. For any component with both positive and negative legs, the positive leg of the component is termed the **anode** and the negative leg is termed the **cathode**. On LEDs, the anode is longer than the cathode. However, for other types of diodes, the cathode is marked with a line. You can remember this because in the schematic of a diode, the cathode has the blocking line.

The diode performs two fundamental “actions” with electric current. The first action of a diode is to drop voltage by an essentially fixed amount *without* affecting or limiting current. This amount of voltage is called the **forward voltage drop** and it is usually around 0.6 V for more non-LED diodes. Forward voltage is often abbreviated as V_F . For most LEDs, the forward voltage drop depends on the color of the LED, with a red LED dropping about 1.8 V and a blue LED dropping about 3.3 V. The forward voltage drop can vary among the other colors as well.

To remind you, when we say “voltage drop,” we are referring to the difference in voltage between the positive and negative leg of the diode. Therefore, no matter what the voltage is coming into the diode, the voltage coming out of the diode will be that voltage minus the voltage drop.

The second action of a diode is to limit the direction of current to a single direction. With some exception, the diode only allows current to flow one way in the circuit. The “normal flow” of a current through the diode is to flow from the anode to the cathode. Looking at the schematic symbol, current flows in the direction

Figure 8.1: A Diode and Single Resistor Circuit



that the arrow is pointing, and current is blocked from flowing the other way (you can think of the line as a “block” preventing reverse flow).

However, diodes are limited in the amount of reverse flow they can block. At a certain point, diodes reach their **breakdown voltage**. The breakdown voltage is the voltage at which they will stop blocking voltage. In regular diodes, this is a failure mode and the precise value shouldn’t be relied upon (we will see an exception to this with Zener diodes). Usually, though, this value is high enough not to worry about (i.e., around 100 volts).

8.2 Circuit Calculations with Diodes in Series

Now let’s talk about how to properly calculate the behavior of circuits with diodes. Remember, the key to a diode is that if current is flowing through the diode, the voltage drop across the diode will be essentially constant. For a normal non-LED diode, this voltage drop is almost always 0.6 V. This is so common it is usually assumed, and never listed in the circuit itself.

Therefore, take a look at the circuit in Figure 8.1. Since the voltage source is 9 volts, that means that the total voltage drop between the positive and negative is 9 volts. The diode will eat 0.6 V of the voltage, but will not limit the current in any way. The resistor, then, since it is the only component left, will use up the rest of the voltage—8.4 V. Therefore, we can calculate the current in the circuit using Ohm’s law:

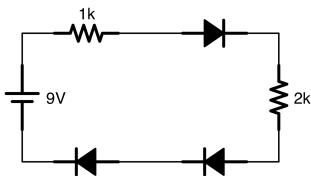
$$I = V/R = 8.4/1000 = 0.0084 \text{ A} = 8.4 \text{ mA}$$

Therefore, our circuit will use 8.4 mA of current. So, as you can see, when doing calculations, the diodes simply provide a drop in voltage, they do not limit current.

This is true no matter how many diodes or resistors I have in my circuit. Figure 8.2 shows a circuit like that. To figure out the behavior of this circuit, remember that *every* diode has a 0.6 V voltage drop. Since the circuit has three diodes, that means that the diodes will drop a total of $0.6 * 3 = 1.8 \text{ V}$.

Therefore, we will have 1.8 V taken up by diodes, which drop voltage without limiting current. Since we have a 9 V source, there will be $9 - 1.8 = 7.2 \text{ V}$ that is not eaten by diodes. This voltage will go to our two resistors. These resistors, even though they are separated by diodes, are essentially in series with each

Figure 8.2: A Circuit with Multiple Diodes and Resistors



other. Therefore, we can treat them as a single resistor in series. So, the total resistance on the circuit will be $1k + 2k = 3k \Omega$.

We can then find the total current running through the circuit using Ohm's Law:

$$I = V/R = 7.2 \text{ V}/3,000 \Omega = 0.0024 \text{ A} = 2.4 \text{ mA}$$

However, it is possible to put too many diodes in your circuit. Since they each eat 0.6 V in their forward voltage drop, that puts a limit on how many you can string together in series from a given battery. For a 9 V battery, if I try to put 20 diodes together in series, I will have used *more* than the total 9 volts that I have available. Therefore, current will not flow. With 20 diodes, the voltage drop will be $20 * 0.6 = 12 \text{ V}$. Since this is more voltage than the battery can put out, no current will flow.

So, we have seen two conditions for which current will not flow through a diode—the first is that the diode will block current from flowing in the wrong direction, and the second is that the diode will not conduct if the voltage source cannot provide enough voltage to bridge the forward voltage drop of the diode.

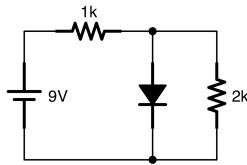
8.3 Circuit Calculations with Diodes in Parallel

The real magic of diodes comes when using them in parallel circuits. Remember the rules that we learned in Chapter 7. Kirchoff's Voltage Law says that between any two points, the voltage drop between those two points will be the same *no matter what path the current follows*. Therefore, since the voltage drop across a diode is *fixed*, that means that we can guarantee a maximum voltage drop between two points on a circuit by putting diodes between them.

Figure 8.3 shows what this looks like. The voltage drop from one side of the diode to the other is 0.6 V. Period. End of story (actually, it could be less, which would keep the diode from conducting altogether, but we won't consider that at the moment).

Kirchoff's Voltage Law tells us that *no matter what path is travelled*, the voltage difference between those two points will be the same. Since the 2k resistor is attached to the same two points that the diodes are attached to, Kirchoff's Voltage Law tells us that the voltage across the resistor *must* be the same as the voltage across the diode. Thus, the voltage across the resistor *must* be 0.6 V.

Figure 8.3: A Single Diode in Parallel with a Resistor



Using Ohm's law, we can deduce the amount of current flowing through that resistor:

$$I = V/R = 0.6/2,000 = 0.0003 \text{ A} = 0.3 \text{ mA}$$

So how much current is flowing through the diode? To find this out, we need to use Kirchoff's Current Law. The amount entering the junction where the diode and the 2k resistor splits off is the same as the amount leaving it. We know that 0.3 mA leaves the junction to go to the resistor. Therefore, if we could figure out how much current was coming *into* the junction we could figure out how much is going through the diode.

To discover that value, we need to know how much current is going through the 1k resistor. To figure that out, we need to know the voltage drop across the resistor. However, we can figure this out easily. Since the tail end of the diode is connected to ground (the negative terminal), that means that after the diode we are at 0 V. Therefore, since the diode voltage drop is 0.6 V, then the voltage before the diode must be 0.6 V. That means that the rest of the voltage must have been consumed by the 1k resistor.

Since the voltage source is 9 V, that means that the voltage for the entire circuit from positive to negative is 9 V, and therefore, the voltage drop across the resistor must have been $9 - 0.6 = 8.4 \text{ V}$. Using this value, we can determine the current going through the resistor using Ohm's Law.

$$I = V/R = 8.4/1,000 = 0.0084 \text{ A} = 8.4 \text{ mA}$$

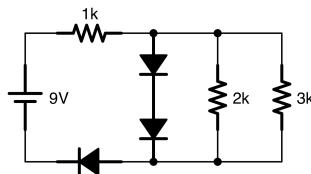
In this circuit, there is 8.4 mA going through the first resistor. That means that there is 8.4 mA coming into the junction. We know that 0.3 mA is going out of the junction through the 2k resistor. That means that the rest of the current is going through the diode. Therefore, we can calculate that the current going through the diode is $8.4 - 0.3 = 8.1 \text{ mA}$.

Diodes don't make the math harder, but they do force you to think a little harder about how you apply the rules.

Let's take a look at a slightly harder example, using Figure 8.4. In this circuit, we have two diodes in parallel with two resistors in parallel. This parallel circuit is in series with a resistor on the front and another diode at the end.

It is almost always easiest to analyze circuits starting with the diodes because their voltage drops are fixed. If we look at this circuit, the diode at the end gives the circuit a voltage drop of 0.6 V.

Figure 8.4: A Circuit with Multiple Diodes



Now let's look at the parallel part of the circuit. Here, we have three pathways—one through two diodes, and two other pathways through resistors. However, one of the pathways contains all diodes. We know that diodes give a constant voltage drop, and we know that Kirchoff's Voltage Law says that all pathways between two points have the same voltage drop. Since we have two diodes, the voltage drop of this parallel pathway is $0.6 * 2 = 1.2 \text{ V}$.

Now we have the parallel resistors to worry about. However, we can use the formula for parallel resistance (Equation 7.2) to figure out the total resistance of the parallel resistors.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{1}{2,000} + \frac{1}{3,000}} \approx \frac{1}{0.0005 + 0.0003333} = \frac{1}{0.0008333} \approx 1200 \Omega$$

However, we technically don't even need that number, because, since we already know the voltage drop across each resistor (it *must* be 1.2 V because of Kirchoff's Voltage Law), we can just apply Ohm's Law to each resistor.

Now, using Ohm's Law, we can calculate the current flowing through the resistors. So, for the 2k resistor, we have:

$$I = V/R = 1.2 \text{ V}/2,000 \Omega = 0.0006 \text{ A} = 0.6 \text{ mA}$$

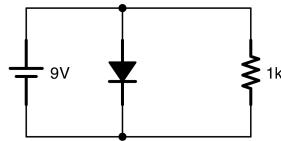
For the 3k resistor, we have:

$$I = V/R = 1.2 \text{ V}/3,000 \Omega = 0.0004 \text{ A} = 0.4 \text{ mA}$$

The total current going into both resistors is simple the sum of each of the currents, $0.4 + 0.6 = 1.0 \text{ mA}$. So there is 1mA total flowing through the two resistors. To find out how much current is flowing through the diode, we will need to know how much current is coming into the circuit itself out of the first resistor.

So how much current is flowing through the first resistor? Well, the voltage drops we have calculated so far include a 0.6 V drop at the end and a 1.2 V drop in the middle. That is a total of $1.2 + 0.6 = 1.8 \text{ V}$. Since the battery is 9 V, that means that there is $9 - 1.8 = 7.2 \text{ V}$ left to be consumed by the circuit. Therefore, that must be the voltage drop of the first resistor. Using Ohm's Law, we find that:

Figure 8.5: A Bad Diode Circuit



$$I = V/R = 7.2 \text{ V}/1,000 \Omega = 0.0072 \text{ A} = 7.2 \text{ mA}$$

Therefore, we have 7.2 mA flowing through that first resistor. So, if we have 7.2 mA coming into the parallel circuit in the middle, and 1 mA flowing to the resistors, the amount of current flowing through the diodes down the middle is $7.2 - 1 = 6.2$ mA. The amount of current going through the final diode is the full 7.2 mA of current in the circuit.

Again, there are a lot of steps, but none of the steps are individually very hard. You simply start with the easiest-to-find values (in this case, the voltage drops from the diodes), and work out from there.

8.4 Diode Short Circuits

Next, let's look at a very bad design with a diode. Let's say that someone wanted to use a diode to regulate the amount of voltage across a resistor to 0.6 V. Therefore, they built the circuit shown in Figure 8.5. Can you figure out what the problem is here?

Well, the voltage drop across the diode will be 0.6 V. However, the battery operates at 9 V. This means that there is 8.4 V left in the circuit with *zero* resistance. Using Ohm's Law, that gives us:

$$I = V/R = 8.4/0 = \infty$$

Thus, having a diode going direct from the positive to the negative of your voltage source is essentially the same as a short circuit. That is why the circuit is bad! To use a diode, there must *always* be resistance somewhere in series with the diode whether the resistance comes before it or after it in order to dissipate the current from the excess voltage.

8.5 Non-Conducting Diodes

There is one case where diodes do not maintain a constant voltage drop, and that is where there is not enough voltage to go across them. Figure 8.6 shows an example of this.

Figure 8.6: Nonconducting Diodes

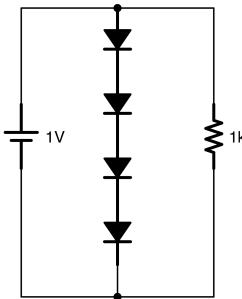
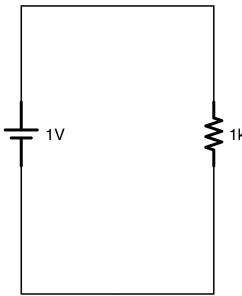


Figure 8.7: A Circuit Equivalent to Figure 8.6 Because of Nonconducting Diodes



In this figure, the voltage drop across the center diode bridge is $0.6 + 0.6 + 0.6 + 0.6 = 2.4$ V. However, the battery source is only 1 V. Since the voltage drop of the diodes is larger than the available voltage, this part of the circuit is basically turned off. In reality, there is a small but ignorable leakage current (about 0.00000022 mA in this case), but we can think of this circuit as effectively switched off.

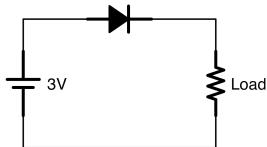
So keep that in mind—if you ever wind up with more forward voltage drop from a diode than you have available voltage, you may treat the diode as if it were an open (i.e., unconnected) circuit—as if it were not even there.

Therefore, we would analyze Figure 8.6 as if it were just like Figure 8.7.

8.6 Usage of Diodes

Diodes can be thought of as circuit traffic cops—they regulate the flow of electricity. They make sure that everything within a circuit is happening in a controlled manner. They regulate the circuit in two different

Figure 8.8: A Simple Diode Protection Circuit



ways—both by limiting the direction of current and, in parallel circuits, by establishing fixed voltages between two points.

The simplest usage of a diode is to use it as a device that makes sure that your battery is in the right direction. If you have a device that will be damaged if someone puts the battery in backwards, a simple diode will make sure that the current can only flow in one direction.

The circuit in Figure 8.8 shows what this looks like. Note that we have a resistor labelled “load.” Many times in circuits, a load resistor is shown to represent whatever else is happening in another part of a circuit. Thus, this circuit shows that the diode is protecting the rest of the circuit (whatever it is) from the user putting the battery in backwards. However, this has a cost—the diode will eat 0.6 V in order to provide this protection.

Another problem often solved by diodes is voltage regulation. Because diodes provide a fixed voltage drop between two points, you can use diodes to ensure a fixed voltage for devices that require it.

For instance, when we looked at batteries in Chapter 6, we noted that their voltage actually varied quite a bit. A 9 V battery might give you anywhere from 7 V to 9.7 V. This is true of any battery, not just the 9 V variety.

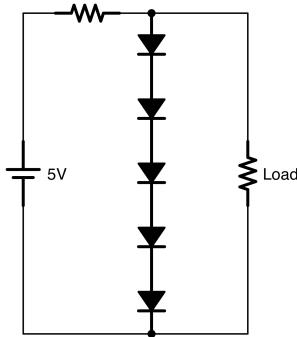
Therefore, if you need a fixed amount of voltage, you can use diodes to provide that at the cost of some extra current.

Figure 8.9 shows a simple voltage regulator using diodes. Given a 5 V battery (actually, a battery of any size significantly over 3 V will work), this circuit will provide a regulated 3 V of electricity to whatever is connected to it as a load (remember, a “load” resistor is just a stand-in for whatever we want to attach to this).

Because the diodes provide a fixed voltage drop of 0.6 V each, then that pathway has a total voltage drop for five diodes as $5 * 0.6 = 3.0$ V. Kirchoff’s Voltage Law says that between two points, *every* pathway between them will have the same voltage drop. This means that the load, since it is connected to those two points, will have the same voltage drop, thus regulating the amount of voltage used by the load.

But what about that first resistor at the beginning of the circuit? Remember, if we provide a pathway through diodes only, we create a short circuit in the system. There has to be some element (usually a resistor) that eats up whatever voltage is left over. Therefore, putting a small resistor before our diode pathway will give the circuit a place to use the excess voltage, and limit the amount of current that flows.

Figure 8.9: A Simple 3 V Voltage Regulator



The size of the resistor will depend on how much current the load requires and how much current you are willing to waste. A small resistor wastes more current, but allows for a higher maximum current used by the load. A larger resistor wastes less current, but if the load needs a lot of current, it could interfere with the voltage regulation.

To see how this could happen, let's say that our load is equivalent to $1,000\Omega$. This means that the amount of current that the load will draw can be calculated using Ohm's Law:

$$I = V/R = 3\text{ V}/1,000\Omega = 0.003\text{ A} = 3\text{ mA}$$

So the load will use up 3 mA of current. That means that, however much current goes through our first resistor, however much that is over 3 mA will be drained off through the diodes. So, let's calculate what that looks like on a tiny, 20Ω resistor. The voltage will be $5 - 3 = 2\text{ V}$.

$$I = V/R = 2\text{ V}/20\Omega = 0.1\text{ A} = 100\text{ mA}$$

So, if we just used a 20Ω resistor, that means that even though the load only used 3 mA, the whole circuit will be using 100 mA to operate! Therefore, we need a bigger resistor to limit the amount of current we use. Let's try a 500Ω resistor:

$$I = V/R = 2\text{ V}/500\Omega = 0.004\text{ A} = 4\text{ mA}$$

This is much better—we are only using 4 mA in this circuit, so we are only wasting 1 mA. There has to be *some* amount of waste to do the voltage regulation.

Let's say that, after a while, our battery sags down to only providing 4 V of power. What happens now? Well, using the 500Ω initial resistor, that means that there is only 1 V extra to drain off, so the current will be:

$$I = V/R = 1 \text{ V}/500 \Omega = 0.002 \text{ A} = 2 \text{ mA}$$

Here, the current is only 2 mA, but we need 3 mA to power the circuit! Thus, if we use a 500Ω resistor, we can't handle our power supply dropping down to 4 V.

What about using the 20Ω resistor? In this case, Ohm's Law would give us:

$$I = V/R = 1 \text{ V}/20 \Omega = 0.05 \text{ A} = 50 \text{ mA}$$

So, here, the 20Ω resistor will still provide plenty of excess current to allow our regulator to keep working. However, it is still eating up an extraordinary amount of current compared to our load.

So how do you choose the right resistor? The way to work situations like this is to think about what are the maximum cases you are designing for, and then calculate appropriately. So, if I want this circuit to work when the battery sags down to 4 V, I need to decide how much excess current I'm willing to have at that level. Let's say I decide that I always want at least half a milliamp to run through the diode (somewhat of an arbitrary number, but if the diode has no power, it is not providing any regulation—this is a low number that is still “noticeable” on the circuit). That means that, since my load will be using 3 mA, the total amount of current running through the initial resistor will be 3.5 mA, or 0.0035 A. Therefore, I calculate what the resistor will need to be a 4 V using Ohm's Law:

$$R = V/I = 1 \text{ V}/0.0035 \text{ A} \approx 286 \Omega$$

Therefore, for this situation, the initial resistor should be 286Ω . Now, let's figure out how much current this wastes when the battery is at full charge—5 V (which means that there will be a 2 V drop across this resistor).

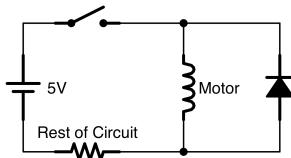
$$I = V/R = 2 \text{ V}/286 \Omega \approx 0.007 \text{ A} = 7 \text{ mA}$$

So, at full charge, there is 7 mA going through this resistor, which means we will waste 4 mA. Whether or not that is acceptable to your circuit depends on what you are going to do with it!

Note that there are better means of regulating battery voltage for a whole circuit than using diodes. However, many times you need a regulated voltage somewhere *within* a more complex circuit. Diodes are great for that, and the same calculations apply.

One final note—as mentioned earlier, although we think of diodes as providing a fixed voltage, they actually do vary a little bit with the amount of current flowing through them. In any circuit, you should allow for $\pm 10\%$ variance in the voltage drop of a diode.

Figure 8.10: A Diode Protection Circuit



8.7 Other Types of Diode Protection

Diodes can provide other types of protection for circuits as well. As single-direction control valves, they can be used to prevent a variety of over-voltage conditions. Often times they are wired in such a way that they will not normally conduct, but will conduct under certain conditions to redirect extra voltage in a safe manner.

Figure 8.10 shows an example circuit. In this circuit, a DC motor is connected to a switch. Notice the diode that is wired backwards. Normally, this diode does absolutely nothing because the current is flowing in the other direction, so it just goes through the motor. DC motors, however, tend to generate very large voltages for a short time when switched off. Therefore, when this motor is switched off the motor can produce a very large voltage—up to 50 V in this circuit!

To protect the rest of the circuit from this sudden influx of voltage, the diode provides an alternative path back through the motor. Thus, when the voltage starts to build up after the switch closes, the diode provides a safe pathway back through motor for it to flow, allowing the voltage buildup to slowly dissipate through the motor, rather than overloading a circuit expecting 5 V with 50 V.

Often times when looking at circuit diagrams you may find diodes in funny places, and oriented in funny ways. These are oftentimes providing some sort of protection to the circuit from potential failure conditions or exceptional circumstances. Many microchips, for instance, use diodes to shunt off excess voltage from static electricity shocks.

8.8 Zener Diodes

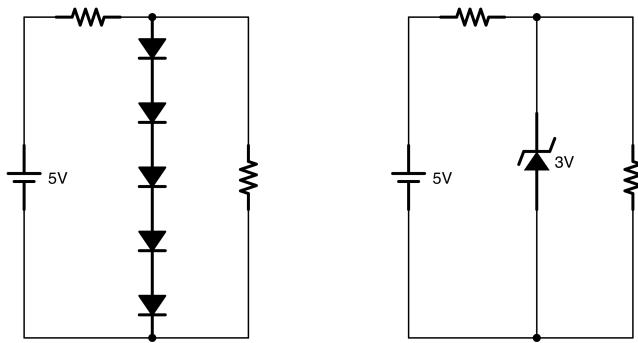
One problem with using diodes for voltage regulation is that their forward voltage drop is pretty small, so you have to have quite a few of them to regulate larger voltages. Zener diodes can help out in these situations. Figure 8.11 shows the symbol for a Zener diode.

Remember that most diodes have a breakdown voltage if you try to pass voltage the wrong way. However, in most diodes, this is a failure mode—doing this can, at best, be unpredictable, and, at worst, damage your diode. A Zener diode, however, is built so that it has a very predictable operation at its breakdown voltage. In fact, at its breakdown voltage, it acts like a normal diode with a larger voltage drop.

Figure 8.11: The Zener Diode Schematic Symbol



Figure 8.12: A Circuit Regulated by Regular Diodes and a Zener Diode



However, since you are using the breakdown voltage rather than the forward voltage, Zener diodes are wired into your circuit *backwards*. Figure 8.12 shows what this looks like. In this figure, on the left you have the same 3 V regulated circuit as above. On the right, you have an equivalent circuit regulated by a Zener diode instead. Since we are using the Zener diode's breakdown voltage rather than its forward voltage, it has to be wired backwards for it to work.

Not only that, the breakdown voltage drop for a Zener diode is much more constant over a larger range of current than the forward voltage drop of most regular diodes. Because of this, Zener diodes are used much more often for voltage regulation than series of regular diodes.

Zener diodes come in a variety of breakdown voltages. In any exercise in this book which involves drawing a circuit with a Zener diode, you may presume that the Zener diode with the voltage drop you are looking for exists. When drawing a circuit, be sure to label the Zener diode with the breakdown voltage you are needing.

Review

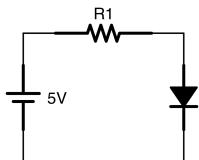
In this chapter, we learned:

1. Diodes only allow current to flow in one direction.
2. Diodes have a fixed forward voltage drop across the diode—0.6 V for normal diodes, and a range of about 1.8 – –3.3 V for LEDs.
3. Different color LEDs have different voltage drops.
4. Diodes also have a breakdown voltage—the amount of voltage for which, if applied in the reverse direction, the diode will no longer block current.
5. When analyzing circuits with diodes, it is often easier to analyze the diodes first, since the voltage drop is fixed.
6. Because of Kirchoff's Voltage Law, anything wired in parallel with diodes will have the same voltage drop as the diodes.
7. If the forward voltage drop on a diode is greater than the available voltage in the circuit, the diode will not conduct and it can be treated as an open circuit.
8. If diode(s) are connected to the positive and negative terminals of a voltage source (such as a battery) with no resistance in series, this will create a short circuit, causing extremely large amounts of current to flow through the diode.
9. Diodes are often used to regulate the amount of voltage between two points on a circuit.
10. Diodes are often used as control valves to regulate the direction of current flow on a circuit.
11. Diodes can be used as voltage regulators to provide a predictable amount of voltage to a circuit with changing battery conditions.
12. The series resistor used with voltage-regulating diodes determines both how much current is wasted and how much current the load can draw—lower-value resistors waste more current but allow the load to draw more current, and higher-value resistors waste less current but don't allow as much potential current to your load.
13. When designing circuits, it is often useful to account for the most extreme variations possible. This will allow your circuit to be more flexible.
14. Diodes can also provide protection to circuits against strange failure conditions, such as voltage spikes and static electricity. Diodes in strange places in circuit diagrams are often there to protect the circuit against certain types of failures or events.
15. Zener diodes are built so that they have very reliable operation on their breakdown voltage.
16. Wiring a Zener diode backwards gives you the equivalent of several forward diodes in series, and can be used for simple voltage regulation.

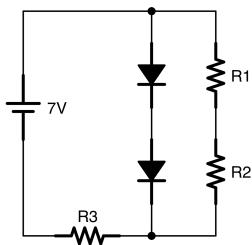
17. The breakdown voltage of a Zener diode is much more constant than the forward voltage of a regular diode, and therefore works even better for voltage regulation.
18. Zener diodes come in a wide variety of breakdown voltages and are usually labelled on the circuit with the necessary breakdown voltage.

Apply What You Have Learned

1. If you have a 9 V voltage source, a blue LED, and a 500Ω resistor all in series, how much current is running through the LED?
2. If you have a 3 V voltage source and a red LED, what size resistor do you need to put in series with the LED to have it use 3 mA of current?
3. If you have a 10 V voltage source, a blue LED, a red LED, and a 200Ω resistor all in series, how much current is running through the LEDs?
4. If I have a 12 V voltage source, a blue LED, and a red LED, and the LEDs have a maximum current of 30 mA before it breaks and a minimum current of 1 mA before it turns on, what range of resistors can I put in series with the LEDs to get them to light up without breaking?
5. In the circuit below, calculate the how much current flowing through each component and each component's voltage drop if R_1 is 500Ω .



6. Let's say instead of a standard diode, the diode is a blue LED. Recalculate the current going through each component and the voltage drops for each component.
7. In the circuit below, calculate how much current is flowing through each component and each component's voltage drop if R_1 is 300Ω , R_2 is 400Ω , and R_3 is 500Ω .



8. Draw a circuit that provides a 6-volt regulated power supply to circuit load from a 9-volt battery using regular diodes. Choose a resistor that works efficiently for a circuit load of 500Ω and operates with a battery voltage from 7V to 9.6V. What is the current at the lowest and highest ranges of the battery? How much is used by the circuit load and how much is wasted through the diodes in each configuration?
9. Draw an equivalent circuit to the previous question using a Zener diode instead of normal diodes.

Chapter 9

Basic Resistor Circuit Patterns

When most people look at a schematic drawing, all they see is a sea of interconnected components with no rhyme or reason combining them. However, most circuits are actually a collection of **circuit patterns**. A circuit pattern is a common way of arranging components to accomplish an electronic task. Experienced circuit designers can look at a circuit and see the patterns that are being used. Instead of a mass of unrelated components, a circuit designer will look at a schematic and perceive a few basic patterns being implemented in a coherent way.

In this chapter, we are going to learn three basic resistor patterns, and learn to work with switches as well.

9.1 Switches and Buttons

Switches and buttons are very simple devices, but nonetheless we probably need to take a moment to explain them. A switch works by connecting or disconnecting a circuit. A switch in the “off” position basically disconnects the wires so that the circuit can’t complete. A switch in the “on” position connects the wires.

There are different types of switches depending on their operation. The ones we are concerned with are called “single pole single throw” (SPST) switches, which means that they control only one circuit (single pole), and the only thing they do is turn it on or off (single throw).

Figure 9.1: Schematic Symbols for an SPST Switch (left) and an APST button (right)



Figure 9.2: A Simple Switch Circuit

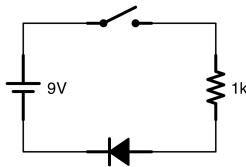


Figure 9.3: A Circuit with Multiple Switches

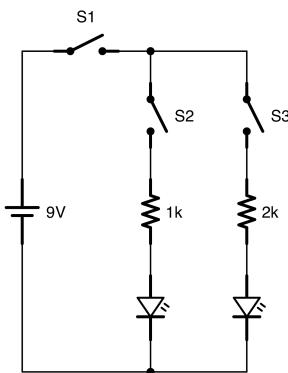


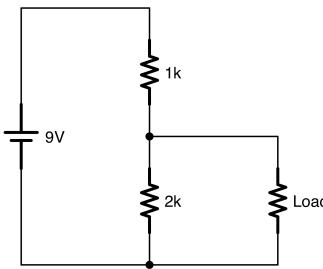
Figure 9.1 show what the schematic symbols for an SPST switch and an SPST momentary switch (i.e., a button) look like. As the drawing indicates, when the switch is open, the circuit disconnects. When the switch closes, it connects the circuit. While the switch holds its position stable (someone has to manually switch it back and forth), the button only connects the circuit *while it is being pushed*. While the button is being pushed, the circuit is connect, but as soon as someone stops pushing the button, the circuit opens back up.

Figure 9.2 shows what a simple circuit with a switch looks like. It is just like a normal LED circuit, but with a switch controlling whether or not electricity can flow. Note that the switch is just as effective on the other side of the circuit. If the switch was the last part of the circuit, it would be equally as effective. Remember, in order for current to flow, there must be a full circuit from positive back to negative.

Switches can also be used to turn on or off individual parts of a circuit—basically reconfiguring the circuit while it is running. In the circuit given in Figure 9.3, a master switch (S1) turns the whole circuit on or off, and two individual switches (S2 and S3) turn parallel branches of the circuit on and off.

To analyze a circuit with switches, you need to analyze the way the circuit behaves with each configuration of switches. In this case, obviously when S1 is open, no current at all flows. However, this circuit will use different amounts of current when S1 is closed, S2 is closed, and both S1 and S2 are both closed. Therefore, to truly know the behavior of the circuit, you need to calculate the current usage in each of these situations.

Figure 9.4: A Simple Voltage Divider Circuit



9.2 Current-Limiting Resistor Pattern

The first resistor pattern we are going to learn is one that we already know—the current-limiting resistor pattern. The idea behind this pattern is that a resistor is added to limit the amount of current that can flow through a device. The size of the resistor needed depends on the size of the voltage source, the action of the device itself, and the maximum amount of current to allow. Then, the resistor size needed can be calculated using Ohm's Law.

Many resistors are added to circuits to limit current flow. At the beginning, we used resistors to make sure we didn't destroy our LEDs. In Chapter 8, we used a resistor to limit the amount of current flowing through our voltage regulation circuit.

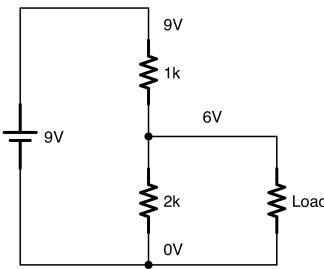
In many different circuits, we will need resistors to limit current for two different reasons—to avoid breaking equipment and to save battery life. Oftentimes, we are actually choosing resistor values to accomplish both of these tasks.

If an LED breaks with 20 mA, then we need a resistor big enough to keep the current that low. However, if the LED light is sufficiently visible with 1 mA, then, to save battery life, we might want a bigger resistor. Battery capacity is often measured in milliamp-hours (mAh), with a typical 9 V battery holding 400 mAh. So, with such a battery, an LED circuit at 10 mA will drain the battery in 40 hours ($400\text{mAh}/10\text{mA} = 40\text{h}$), but the same LED circuit with a bigger resistor, limiting the current to 1 mA will take a full 400 hours ($400\text{mAh}/1\text{mA} = 400\text{h}$) to drain the same battery! That will save you a lot of money in the long run.

9.3 Voltage Divider Pattern

A **voltage divider** occurs anytime there are two resistors together with a subcircuit coming out from in-between them. They usually are connected to a fixed positive voltage on one side of the first resistor, and the ground on the other side of the second resistor, but this isn't strictly necessary. A simple schematic of a voltage divider is shown in Figure 9.4. Notice that there are two resistors between the voltage source and the ground (a 1k on top and a 2k on bottom) and a subcircuit (indicated by the load resistance) branching

Figure 9.5: Voltage Divider with Voltages Labelled



off from between them. Under certain circumstances (which will be covered in a moment), we can basically ignore the parallel resistance of the subcircuit, and just look at the voltages at each point in the main voltage divider circuit.

We can see that the voltage at the top of the voltage divider is 9 V (because it connects to the positive terminal) and at the bottom of the voltage divider it is 0 V (because it connects to the negative terminal). Therefore, the total voltage drop across both resistors must be 9 V. Since the resistors are in series (remember, we are ignoring the load for now), we can find the total resistance in the circuit by just adding their resistances. So, $1,000\Omega + 2,000\Omega = 3,000\Omega$. Since the current in a series is the same for the whole series, we can now use Ohm's Law to calculate the current flow:

$$I = V/R = \frac{9\text{ V}}{3,000\Omega} = 0.003\text{ A} = 3\text{ mA}$$

So, there is 0.003 A (3 mA) in this circuit. That means that *each* resistor in the series will have this amount of current flowing through them. Therefore, we can calculate the voltage drop across each resistor. Let's look at the 1k resistor:

$$V = I * R = 0.003\text{ A} * 1,000\Omega = 3\text{ V}$$

So, the voltage drop across the first resistor is 3 V. That means that, since the battery started at 9 V, at the end of the resistor the voltage compared to ground is 6 V. We can calculate the voltage drop across the second resistor either by Ohm's Law again or just by noting the fact that since the other end of the resistor is connected to ground, the voltage *must* go from 6 V to 0 V.

Figure 9.5 shows the voltages at each point. As you can see, the wire from the middle of the voltage divider has a new voltage that can be used by the load. This is what voltage dividers are normally for—they provide a simple way of providing a scaled-down voltage to a different part of the circuit.

But how do we choose the values of the resistors?

One thing to note is that the second resistor consumed exactly twice as much voltage as the first resistor.

Additionally, the second resistor was exactly twice as large as the first resistor. Thus, as a general principle, the relative sizes of the resistors will determine the relative amounts of voltage they eat up. So, if we needed a 4.5 V output, that is half of our input voltage. Therefore, we would need both resistors to be the same.

A more explicit way of stating this is with an equation. Given a starting voltage V_{IN} connected to the first resistor, R_1 , and the second resistor (R_2) connected to ground, the output voltage (V_{OUT}) coming out between the resistors will be given by the equation:

$$V_{OUT} = V_{IN} * \frac{R_2}{R_1 + R_2} \quad (9.1)$$

Note that the specific values don't matter yet—it is the *ratio* we are concerned about so far. To get 4.5 V, we can use two 1 kΩ resistors, two 200 Ω resistors, or two 100 kΩ resistors. As long as the values are the same, we will divide the voltage in half.

If we wanted an 8 V output, we would do a similar calculation. Since we start at 9 V, we need to use up $\frac{1}{9}$ of the voltage in the first resistor, and $\frac{8}{9}$ of the voltage in the second resistor. Therefore, our resistors need to be in similar ratio. We could use an 100 Ω resistor for the first resistor, and a 800 Ω resistor for the second resistor.

So how do you determine exactly what value to use? Here is where we start thinking about the load again. While we have been treating the voltage divider as a series circuit, in truth we have one resistor in series, and then a parallel circuit with the other voltage divider resistor in parallel with the load. Our simplified model (where we ignore the parallel resistance) will work, *as long as the load resistance does not impact the total parallel resistance by a significant amount*. Therefore, let's look at how the load resistance affects the parallel resistance.

So, using Equation 7.2 we can write a formula for the total resistance of these two, with R_2 being our second voltage divider resistor and R_L being our load resistance:

$$R_T = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}}$$

Now, let's look back at the circuit in Figure 9.5. Let's say that the resistance of the load (R_L) is 400 Ω, which is much less than the resistance of the voltage divider resistor (R_2). So what is the total resistance?

$$R_T = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}} = \frac{1}{\frac{1}{2,000} + \frac{1}{400}} = \frac{1}{0.0005 + 0.0025} = \frac{1}{0.003} \approx 333 \Omega$$

This is way off of our simplified model which ignored the load resistance, which gave 2,000 Ω. Now, let's increase the load resistance so that it is equal to the load resistance (2,000 Ω) and recalculate:

$$R_T = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}} = \frac{1}{\frac{1}{2,000} + \frac{1}{2,000}} = \frac{1}{0.0005 + 0.0005} = \frac{1}{0.001} \approx 1,000 \Omega$$

This is still significantly off, but it is much closer. So, now, let's look at what happens if the load resistance is double of R_2 , or 4,000 Ω :

$$R_T = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}} = \frac{1}{\frac{1}{2,000} + \frac{1}{4,000}} = \frac{1}{0.0005 + 0.00025} = \frac{1}{0.00075} \approx 1,333 \Omega$$

Here, we are getting much closer to our original value. Now, let's say that the load is ten times the resistance of our R_2 resistor, or 20,000 Ω . That give us this:

$$R_T = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}} = \frac{1}{\frac{1}{2,000} + \frac{1}{20,000}} = \frac{1}{0.0005 + 0.00005} = \frac{1}{0.00055} \approx 1,818 \Omega$$

This is very close to the resistance of R_2 by itself. So, what we can say is that our voltage divider circuit can ignore the resistance of the load *if the resistance of the load is significantly more than the resistance of the voltage divider resistor*. A way of writing this down is that $R_L \gg R_2$. What “significantly” means depends on how sensitive your circuit it to voltage changes, but, generally, I would say that R_L should be at least ten times R_2 .

So, for low-resistance loads, a voltage divider does not work well, because it puts too little resistance between the voltage source and ground. However, in Chapter 11 we will see that many circuit have loads of approximately infinite resistance, so voltage dividers work well.

In general terms, a voltage divider with smaller resistors is “stiffer” because it varies less in response to variations in a load, but it also eats up more current. A voltage divider with larger resistors doesn’t work with low-resistance loads, but it also uses up much less current.

9.4 The Pull-Up Resistor

The pull-up resistor is a strange circuit, but we will find very good applications for it once we start dealing with ICs in Chapter 11. It is probably easiest to describe by simply showing you a circuit and then describing how it works.

Figure 9.6 shows the circuit diagram for a basic pull-up resistor circuit. Normally, we think of lighting up an LED by pushing the button. However, in this case, pushing the button causes the current to bypass the LED.

If you look at the path from where the circuit branches, when the button is not pressed, the current can only go one way—through the LED. However, when the button is pressed, the electricity has two options—either through the LED or directly to ground through the button. The electricity would always rather go directly to ground rather than through an intermediary, so *all* of the current goes through the closed button, and none of it goes through the LED.

Since the branch point is directly connected to ground when the button is pushed, that means that the

Figure 9.6: Basic Pull-Up Resistor

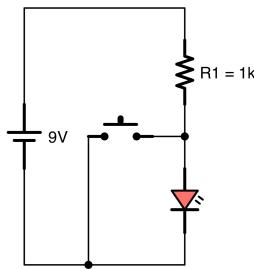
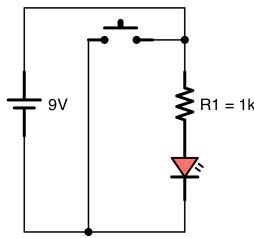


Figure 9.7: Incorrect Way to Wire the Circuit



voltage *at the branch point* is also zero. Kirchoff's Voltage Law says that no matter what path is taken, the voltage drop will always be the same. However, an LED induces a voltage drop, but the voltages on both sides of the LED are zero. Therefore, electricity cannot flow through the LED.

So what is the function of the resistor? The resistor connects the switch and the LED to the positive voltage source, and provides a limitation on the current that runs through it. The resistor must be *before* the branch point for it to work.

Think about what happens without the resistor, or if the resistor is after the branch point. The electricity will have a path directly from the positive voltage source to ground with no resistance—in other words, a short circuit. This will draw an enormous amount of electricity. Figure 9.7 shows what this would look like. Notice that when the button is pushed, you can trace a path from the positive voltage source to ground with no intervening resistance.

The resistor is called a pull-up resistor because it is connected to the positive voltage source, and is used to “pull up” the voltage on the circuit to a positive value when the switch is open.

In short, a pull-up resistor is usually used to supply positive voltage to a circuit which might be turned off by redirecting the voltage to ground. The resistor provides both the electrical connection to the positive source and a limit to the amount of current that will flow if the wire is then routed to ground (usually through some kind of switching mechanism).

9.5 Pull-Down Resistors

One more basic resistor circuit that is often used is the pull-down resistor. While the pull-up resistor is connected to the positive power rail, the pull-down resistor is instead connected to ground. So, in a pull-up resistor, if part of the circuit is disconnected, the voltage goes high. In a pull-down resistor, if part of the circuit is disconnected, the voltage goes low. However, we don't yet have enough background really to understand how they are used here. They are covered more fully in Chapter 12. They are merely mentioned here because they are one of the basic resistor circuit patterns that are seen throughout electronics.

Review

In this chapter, we learned:

1. Buttons and switches allow circuits to be altered while they are running by connecting circuits (allowing pathways for electricity) and disconnecting circuits (blocking pathways for electricity).
2. Most circuits are a combination of common, well-understood circuit patterns.
3. The more experienced you are with circuits, the easier it is to see these circuit patterns when you look at a schematic drawing.
4. A current-limiting resistor is a resistor that is used to limit the maximum current flow within a circuit, either to protect other components or to limit overall electricity usage.
5. A voltage divider is a pair of two resistors connected in series with one another (usually connected to a positive voltage on one side and the ground on the other), but with another wire coming out in-between them to provide voltage to another circuit (called the *load*).
6. In a voltage divider, it is assumed that the resistance of the load is significantly more than the resistance of the second half of the voltage divider because then the load can be basically ignored for calculating voltage drops.
7. For a voltage divider, the ratio of the voltages consumed by each resistor is the same as the ratio of their resistances. The output voltage coming out between them is the same as the voltage used by the second resistor.
8. Another way of stating the output voltage is $V_{OUT} = V_{IN} * \frac{R_2}{R_1+R_2}$, where R_1 is the resistor connected to the positive voltage and R_2 is the resistor connected to ground.
9. Voltage dividers with smaller resistances are “stiffer”—they are impacted less by the resistance of the load. Voltage dividers with larger resistances waste much less current.
10. A pull-up resistor circuit is a circuit in which a positive voltage which may be switched to ground at some point is provided through a resistor.
11. The pull-up resistor both (a) connects the circuit to the positive voltage to supply a positive current when the circuit is not switched to ground and (b) limits the current going to ground (i.e., prevents a short circuit) when the load is switched to ground.
12. It is called a pull-up resistor because it pulls the voltage up when the circuit is not switched to ground.

Apply What You Have Learned

1. In Figure 9.3, calculate the amount of current used by the whole circuit for each configuration of the switches S2 and S3 when S1 is closed. You can assume that the LEDs are red LEDs.

2. Build the circuit given in Figure 9.3 (you may swap out resistors with different but similar values—anything from 300Ω to about $5\text{k}\Omega$ should work).
3. Given a 15 V voltage supply, what size of a resistor would be needed to make sure that a circuit never went over 18 mA.
4. Given a 9 V battery source, design a voltage divider that will output 7 V to a load that has a resistance of $10\text{k}\Omega$.
5. Given a 3 V battery source, design a voltage divider that will output 1.5 V to a load that has a resistnace of $1\text{k}\Omega$.
6. In Figure 9.6, how much current is going through the circuit when the switch is open? How much when it is closed?
7. How would you modify the circuit in Figure 9.6 to keep the maximum current in the circuit under 2 mA? Draw the full circuit out yourself.
8. Build the circuit you designed in the previous question. If you do not have the right resistor values, use the closest ones you have.

Chapter 10

Understanding Power

So far we have covered the basic ideas of voltage, current, and resistance. This is good for lighting up LEDs, but for doing work in the real world, what is really needed is **power**. This chapter on its own adds very little to your capabilities as a circuit designer, but it is absolutely critical background information for the chapters that follow. Knowing about power, power conversions, and power dissipation will be critical to taking your electronics abilities into the real world.

10.1 Important Terms Related to Power

To understand what power is, we need to go through a few terms from physics (don't worry—they are all easy terms):

1. **Work** happens when you move stuff.
2. Work is measured in **joules**. A joule is the amount of work performed when a 1 kilogram object is moved 1 meter.
3. The capacity to perform work is called **energy**. Energy is also measured in joules.
4. **Power** is the sustained delivery of energy to a process.
5. Power is measured **watts** (abbreviated W). Watts are just the number of joules per second.
6. Another measurement of power is horsepower (abbreviated hp). 1 horsepower is equivalent to 746 watts. Horsepower is not important for electronics, but I wanted to mention this because horsepower is a term you have probably heard, and I wanted you to be able to connect its importance.

One of the interesting things about work, energy, and power is that they can take on a number of forms that are all equivalent. For instance, we can have mechanical energy, chemical energy, and electrical energy (as

well as others). We can also perform mechanical work, chemical work, and electrical work. All these types of energy and work can be converted to each other. They are all also measured in joules. Therefore, we have a common unit of energy for any sort of task we want to accomplish.

Now, when we actually apply energy to perform work, we do not get a 100% conversion rate. That's because the process of conversion is **inefficient**—not all of the energy gets directed to the task we want to perform. There is no perfectly efficient process of converting energy to work. Additionally, there is no way to create energy from nothing—any time you need additional energy you will need a source for it.

When energy is converted to work, *all* of the energy does something, even if it isn't work on the task you want. Usually, the inefficiencies get converted to **heat**. So, if I have a process that is only 10% efficient, and I give that process 80 joules of energy, then that process will do only 8 joules of work, leaving 72 joules of energy that is converted to heat.

Work and energy are usually used for systems that do one thing and then stop at the end. In electronics, we are usually building systems that stay on for long periods of time. Therefore, instead of measuring energy, we measure power, which is the continuous delivery of power (or usage of power in doing work).

As we mentioned, power is measured in watts, which is 1 joule per second. So, if you have a 100 W light bulb, that bulb uses 100 joules of energy each second. 100 W light bulbs are very inefficient, which is why they get so hot—the energy that is not converted to light gets converted to heat instead.

10.2 Power in Electronics

So, we have a basic idea about what power is in general. In electronics, there are a few equivalent ways of calculating power.

The first is to multiply the number of volts being consumed by the number of amps of current going through a device:

$$P = V \cdot I \tag{10.1}$$

Here, P indicates power measured in watts, V indicates volts, and I indicates current measured in amps. So, if my circuit is on a 9-volt battery, and I measure that the battery is delivering 20 mA to the circuit, then that means I can calculate the amount of power that my circuit is using (don't forget to convert millamps to amps first!):

$$\begin{aligned} W &= V \cdot I \\ &= 9 \text{ V} \cdot 20 \text{ mA} \\ &= 9 \text{ V} \cdot 0.02 \text{ A} \\ &= 0.18 \text{ W} \end{aligned}$$

So, our circuit uses 0.18 watts of power.

You can also measure the amount of power that individual components use. For instance, let's say that a resistor has a 3 V voltage drop and has 12 mA of current running through it. Therefore, the resistor uses up $3 * 0.12 = 0.36$ watts of power.

The second way of calculating power comes from applying Ohm's law. Ohm's law say:

$$V = I \cdot R \quad (10.2)$$

So, if we have the equation $P = V \cdot I$, Ohm's law allows us to *replace* V with $I \cdot R$. Therefore, our new equation becomes:

$$P = (I \cdot R) \cdot I \quad (10.3)$$

Or, we can simplify it further and say that

$$P = I^2 \cdot R \quad (10.4)$$

We can also substitute $I = V/R$ and wind up with a third equation for power:

$$P = V^2/R \quad (10.5)$$

So, if we have 15 mA running through a 200Ω resistor, then we can calculate the amount of power being used using Equation 10.4:

$$\begin{aligned} W &= I^2 \cdot R \\ &= (15 \text{ mA})^2 \cdot 200 \Omega \\ &= (0.015 \text{ A})^2 \cdot 200 \Omega \\ &= 0.000225 \cdot 200 \\ &= 0.045 \text{ W} \end{aligned}$$

Now, if you think about it, the resistor isn't actually *doing* anything. It is just sitting there. Therefore, since we are not accomplishing any *work* by going through the resistor, the energy gets converted to heat. Electronics components are usually rated for how much power they can **dissipate**, or easily get rid of. Most common resistors, for instance, are rated between $1/16 \text{ W}$ and $1/2 \text{ W}$ (most that I've seen for sale are $1/4 \text{ W}$). This means that they will continue to work as long as their power consumption stays under their limit. If the power consumption goes too high, they will not be able to handle the increased heat, and will break (and possibly catch fire!).

Figure 10.1:



So far, our projects have dealt with low enough power that this isn't a concern. In fact, using 9 V batteries, it is hard to generate more than 1/4 W of power—you would have to have less than 350Ω of resistance on the *whole* circuit, and have the entire voltage drop occur on the resistor.

10.3 Handling Power Dissipation with Heat Sinks

As we mentioned earlier, when power dissipates without doing any work, it is converted to heat. Some devices need to dissipate large quantities of heat under regular workloads. One common device that often needs to dissipate heat is the voltage regulator, like the 7805 regulator we encountered in Chapter 12.

The way that this regulator performs its job is essentially by dissipating power until the voltage is at the right level. When used with any serious amount of current, this can actually get very, very hot. As such, the back side of these contains a metal plate which is used to dissipate heat. Additionally, it has a metal tab with a hole that can be used to attach a **heatsink**.

A heatsink is a metal structure with a large surface area that helps an electronic component dissipate heat. By being made of metal, it quickly moves the heat into itself. By having a large surface area, it can transfer the heat to the air, where it will then disperse into the environment.

Figure 10.1 shows a 7805 chip next to its heatsink. To attach the heatsink, just screw it in to the 7805. On the 7800 series of regulators, the tab is electrically connected to ground, so it should not produce a voltage. However, other types of chips in the same TO-220 package may actually have a voltage on the tab. In such a case, it would be wise to buy an isolation kit to electrically isolate the chip from the heatsink, otherwise incidental contact with the heatsink could cause a short circuit.

10.4 Transforming Power

As we have discussed, energy (and therefore power) can be transformed among a variety of forms—mechanical, electrical, chemical, etc., as long as we remember that energy is only reduced or lost, never gained. The essence of energy transformation is at the heart of what makes batteries work. A battery contains energy stored in a chemical form. Chemical reactions in the battery allow electrons to move. By drawing the electrons through a specific path (drawing them to the positive from the negative), this reaction generates electrical energy. So we have a conversion from chemical energy (the reaction of the chemicals in the battery) into electrical energy (the pull of the electrons through the circuit).

This can also go the other way. Electrical energy can be used to stimulate chemical reactions. A common one is the separation of water into hydrogen and oxygen.

It is the same with mechanical energy. In an electric motor, electrical energy is converted into mechanical energy in the motor. But the reverse also can occur. A power generator is made by converting mechanical energy into electrical energy.

We won't go into details on how each of these transformations work (you would need to take courses in chemistry, mechanics, etc. to know more), but the essential ideas are that

1. energy and power can be transformed between a variety of forms,
2. these forms of energy can all be measured with the same measuring stick (joules), and
3. every energy transformation will lose (never gain) some amount of energy through inefficiencies.

Power and energy are known as **conserved quantities**, because, although they are transformed, they are never created or lost. When we talk about power lost through inefficiencies, the power actually isn't lost in total, it is merely converted to heat. You can think of heat as power that is applied in a nonspecific direction.

In Section 10.2, we noted that in electronics, the power (measured in watts) is determined by *both* the voltage and the current—by multiplying them together. Therefore, what will be conserved in electronics will not be the voltage or the current individually, but their product. What this means is that we can, at least in theory, increase the voltage without needing a power gain, but at the cost of current. Likewise, we can, at least in theory, increase the current without needing a power gain, at the cost of voltage. In both of these cases, rather than transforming electrical power to another form of power altogether, we are transforming it into a different configuration of electrical power.

Devices that convert electrical power between different voltage/current configurations are known as **transformers**. A step-up transformer is one that converts a low voltage to a higher voltage (at the cost of current), and a step-down transformer is one that converts a high voltage to a lower voltage (but can supply additional current).

Technically, for DC circuits, these are usually known as **DC-DC power converters** or **boost converters** instead of being called transformers, but the same rules apply—the total number of watts delivered can never increase but the voltage can be converted up and down at the expense of the current. Note that if you

tried to wire a regular AC transformer to a DC power supply, it would not deliver any power at all—DC-DC converters work on very different principles than AC converters.

So, if I had a source of 12 V and 2 A, then I would have a $12 \cdot 2 = 24$ W. Therefore, it may be possible to convert that to 24 V, but I would only be able to get 1 A of current ($24 \cdot 1 = 24$). However, I could drop the voltage to get more current. If I needed 4 A, I could reduce the voltage to 6 V. Also remember that in doing these transformations there is always some amount of power loss as well, but these calculations will give you what the maximum possibilities are.

The actual mechanisms that these devices employ for doing power conversions are outside the scope of this book.

10.5 Amplifying Low-Power Signals

Microcontrollers (like the ATmega328/P) are only capable of processing and generating low-power signals. The ATmega328/P can only source up to 40 mA per pin, and only about 200 mA total across all pins simultaneously. At 5 V, 40 mA would yield a maximum of 0.2 W. Therefore, if you want to turn on a device that requires more power than that, you will need to **amplify** your signal.

Now, as we discussed previously, you can't actually create more power out of nothing. What you can do is, instead of trying to *create* power, you can instead *control* power. We will discuss several specific techniques on how to do this over the next few chapters, but the essential idea is that you can amplify a signal by using a small signal to control a larger one.

Think about your car. The way that you control your car is by taking a low-power signal, such as the gas pedal, and using it to control a high-power signal, such as the engine. My foot is not directly powering the car. My foot is merely using the pedals to tell another power source—the engine—how much of its energy it should move. My foot doesn't actually interact directly with the engine at all, except as a valve to unleash or not unleash the power of the engine.

In the same way, since the output signals from the microcontrollers are low-power, instead of using these signals directly we will use the signals to control larger sources of power. Devices which can do this include devices such as relays, optocouplers, transistors, op-amps, and darlington arrays, some of which will be covered in the forthcoming chapters.

Review

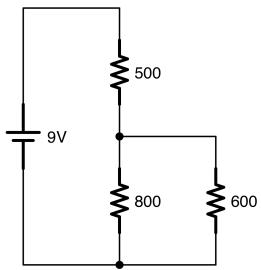
In this chapter, we learned:

1. Work is what happens when you move stuff, and is measured in joules.
2. Energy is the capacity to do work and is also measured in joules.
3. Power is the sustained delivery of energy, and is measured in joules per second, also called watts.
4. Power can be converted to a number of different forms.
5. Converting power to another form or using it to do work always has inefficiencies, and these inefficiencies result in heat.
6. In electronics, power (in watts) is calculated by multiplying the voltage by the current ($P = V \cdot I$). It can also be calculated as $P = I^2 \cdot R$ or $P = V^2/R$.
7. To calculate the power consumption of an individual component, use the voltage drop *of that component* and multiply the current flowing through it.
8. Most components have a maximum rating for the amount of power they can safely consume or dissipate. Be sure your components stay under that limit.
9. Some components can handle additional power dissipation by adding a heatsink, which will more effectively dissipate the excess heat into the air.
10. Power can be transformed into other types of power (mechanical, chemical, etc.), but can never go beyond the original amount of power.
11. Electrical power can also be transformed into different combinations of voltage and current, as long as the total power remains the same.
12. Components that do this transformation are called transformers for AC power, and DC-DC converters for DC power.
13. Because power cannot be created, the way that signals are amplified is by using a small power signal to control a larger power source.

Apply What You Have Learned

1. If I have 50 joules of energy, what is the maximum amount of work I could possibly do with that amount of energy?
2. If I am using up 10 joules of energy each second, how many watts am I using up?
3. If I convert 30 watts of mechanical power into electrical power with 50% efficiency, how many watts of electrical power are delivered?

4. If I have a circuit powered by a 9 V battery that uses 0.125 A, how many watts does that circuit use?
5. If a resistor has a 2 V drop with a 0.03 A current, how much power is the resistor dissipating?
6. If a resistor has a 3 V drop with a 12 mA current, how much power is the resistor dissipating?
7. If a 700Ω resistor has a 5 V drop, how much power is the resistor dissipating?
8. If a 500Ω resistor has 20 mA flowing through it, how much power is the resistor dissipating?
9. In the circuit below, calculate the voltage drop, current, and power dissipation of every component (except the battery).



Part II

Digital Electronics

Chapter 11

Integrated Circuits and Resistive Sensors

So far, the components we have studied are simple, basic components—batteries, resistors, diodes, etc. In this chapter, we are going to start to look at **integrated circuits**, also called **chips**, **microchips**, or **ICs**. An IC is a miniaturized circuit placed on silicon. It is a whole collection of parts geared around a specific function. These functions may be small, such as comparing voltages or amplifying voltages, or they may be complex, such as processing video or even complete computers. A single chip may hold just a few components, or it may hold billions.

Miniaturized circuits have several advantages—they are cheaper to produce in mass, they use less power, and they take up less space in your overall circuit—all because they have a reduced area and use fewer materials. These miniaturized circuits are what allowed for the computer revolution over the last century.

11.1 The Parts of an Integrated Circuit

Integrated circuits, as we have noted, are basically miniaturized circuits placed on a silicon plate, called the die. This die is where all of the action of the integrated circuit takes place.

The die is then placed into a **package**, which then provides connection points for circuit designers to interface with the IC. These connection points are often called **pins** or **pads**. Each pin on an IC is numbered, starting with pin 1 (we will show you how to find pin 1 shortly). Knowing which pin is which is important, because most of pins on a chip each have their own purposes, so if you attach a wire to the wrong pin your circuit won't work, or you will destroy the chip. Most packages are marked with the chip's manufacturer and part number.

There are many different types of packaging available, but there are two general types that are often encountered:

Through-Hole In this packaging type, the connection points are long pins which can be used on a

Figure 11.1: Comparison of the Same IC in SMD (left) and DIP (right) Packages

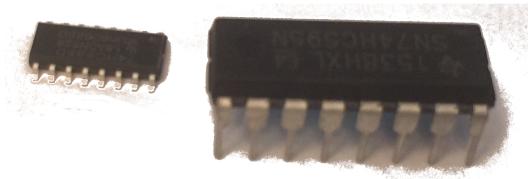


Figure 11.2: Pin 1 is Immediately Counterclockwise of the Notch



breadboard. This type of packaging is easiest for amateur usage.

Surface Mount In this packaging type, the connection points are small pads which are meant to be soldered to a circuit board. These packages are much smaller (and therefore less expensive), and can be more easily managed by automated systems. These are also referred to as SMD (surface mount devices) or SMT (surface mount technology).

Since we are only using breadboards in this book and not doing any soldering, we will only concern ourselves with through-hole packaging. However, through-hole packaging itself comes in a variety of styles. The main one we will concern ourselves with is called a **dual in-line package**, or **DIP**.

An Integrated Circuit in a DIP package has two rows of pins coming out of the package. Most chips mark either the top of the chip with a notch or indentation (where pin 1 is immediately counterclockwise of the notch), or mark pin 1 with an indentation, or both. See Figure 11.2 to see how to use the notch to find pin 1. The rest of the pins are numbered counterclockwise around the chip.

The beauty of a DIP packaged IC is that it fits perfectly onto most breadboards. Figure 11.3 shows how you can place your IC across the breadboard's bridge and each pin on the chip will have its own terminal strip to connect to.

Be careful, though, when inserting ICs into breadboards. The pins on an IC are often slightly wider than the breadboard. If you just jam the IC into the breadboard, you will likely accidentally crush one or more of the pins that aren't exactly aligned on the hole. Instead, compare the width of the pins to the width it

Figure 11.3: A DIP IC Inserted Into a Breadboard

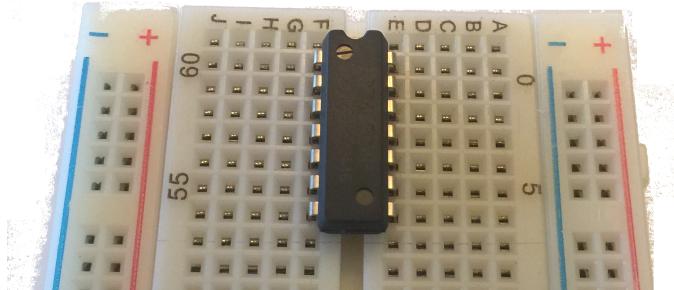
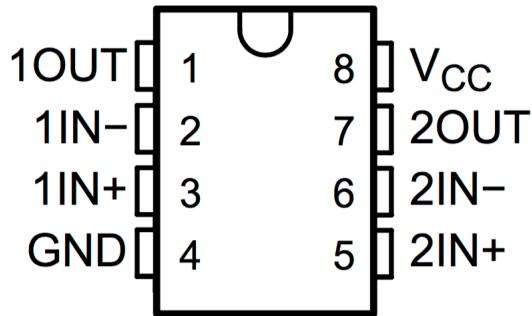


Figure 11.4: The Pin Configuration of an LM393



has to fit in on your breadboard. If it doesn't match up, *very gently* bend the pins with your fingers or with pliers to get them to match up.

Usually, the ICs that I purchase are just a little wide, and I will squeeze the pins on each side slightly between my thumb and finger until they move close enough together. However, you adjust the pins, make sure they line up before pushing them into their connection points on the breadboard. Also, with larger ICs, you may need to adjust the IC back and forth as you gently insert it into place on the breadboard.

11.2 The LM393 Voltage Comparator

There are thousands and thousands of available chips which do a dizzying array of functions. In this chapter, we are going to focus on a very simple chip—the LM393 Voltage Comparator. This chip does one simple task. The LM393 compares two input voltages, and then outputs either a high-voltage signal or a low-voltage signal depending on which input voltage is greater. The LM393 is actually a *dual* voltage comparator, which means that it will do two separate comparisons on the same chip. Like most chips, the LM393 is an *active* device, which means that it additionally requires a voltage source and a ground connection to provide power to the device.

Figure 11.4 shows the pin configuration (also called the **pinout**) of the LM393. The first thing to note on any pinout is where the voltage and ground connections are. In this case, the voltage is marked as V_{CC} and the ground is marked as GND . Even though the LM393 has *two* voltage comparators on the chip, they both share the power (V_{CC}) and ground (GND) pins. The left side of the chip diagram shows the inputs and output for the first voltage comparator ($1IN_+$, $1IN_-$, and $1OUT$), and the inputs and output for the second voltage comparator is on the right ($2IN_+$, $2IN_-$, and $2OUT$). In your projects, you can use whichever one is more convenient for you, or even both at the same time.

So, the $1IN_+$ pin (pin 3) and the $1IN_-$ pins are where the two voltages are being fed that are being compared by the first comparator. The $1OUT$ is the pin which will contain the output. If the voltage at $1IN_+$ is less than the voltage on $1IN_-$, the output pin will be at a low (i.e., zero/ground) voltage. If the voltage at $1IN_+$ is greater than the voltage on $1IN_-$, the output pin *will not conduct at all*, but this will be considered a “high” (positive-voltage) state. This sounds counterintuitive, but, as we will see, this lets us set our own output voltage to whatever we want without causing too much complexity. This configuration where high-voltage outputs don’t conduct is called an **open collector** configuration. Don’t worry if this is a little confusing, we will discuss it more in-depth later in the chapter.

— Voltage Sources on Integrated Circuits

Note that the voltage pins on integrated circuits can be marked in a number of different ways. The positive voltage source is often labelled as V_{CC} , V_{DD} , or V_+ . The ground connect is often labelled as GND , V_E , V_SS , or V_- . There are additional ways that these are labelled as well. Finding the positive and ground connections for an IC should always be the first thing you do with them.

11.3 The Importance and Problems of Datasheets

Every IC (and, usually, any other part as well) has a datasheet supplied by the manufacturer which tells you important details about how you should use their chip in your circuit. Reading datasheets is one of the worst parts of electronics, in my opinion. For me, datasheets rarely have the information I am actually looking for in a way that is easy to find.

In fact, most datasheets assume that you already know how to use the device, and the datasheets are just there to supply additional details about the limitations of the device. For instance, looking through the LM393 datasheet from Texas Instruments, the actual operation of the device isn’t even listed until page 11, and there it is buried within a sub-subsection, almost as a side-note.

These datasheets are written by people who have spent a lot of time being electrical engineers, and they are written for people who have spent a lot of time being electrical engineers, so when mere mortals read the datasheets, the important pieces are often shrouded in unintelligible gibberish. For instance, the fact that the “high” output state of the device doesn’t conduct isn’t mentioned explicitly anywhere at all in the datasheet. Instead, it is implied by the configuration.

The reason for this is that the datasheets are usually read by professionals familiar with the type of device,

and just need to know the electrical details so they don't accidentally bend the device beyond the breaking point. Thus, the datasheets oftentimes spend more time just showing and describing the layout of the circuit on the chip and graphs of different chip properties, and then you are left to interpret what that means for your circuit. For advanced circuit designers, this is great. For students and hobbyists, however, this is oftentimes more frustrating than helpful.

However, datasheets do often provide a few basic details that are helpful to everyone. They will often tell you:

- What each pin does
- What the power requirements are
- What the outer limits of the chip's operation are
- An example circuit that you can build with the device

For all of these reasons, Appendix F contains simplified datasheets for a number of common devices that are easier to read than the standard ones.

For the LM393, the important points are:

1. The input voltage on V_{CC} can be anywhere between 2 V and 36 V.
2. When sensing voltage, the LM393 doesn't really draw any (or at least much) current, so there are no parallel resistances we need to worry about.
3. The output is high when IN^+ is greater than IN^- , and low (i.e., ground) when IN^+ is less than IN^- , with an error range of about 2 millivolts.
4. When the output is low, the output pin will conduct current into itself (since it is at ground, positive charge will naturally flow into it), but if sink more than 6 mA into it, you will destroy it.
5. When the output is high, the device will not conduct any current.

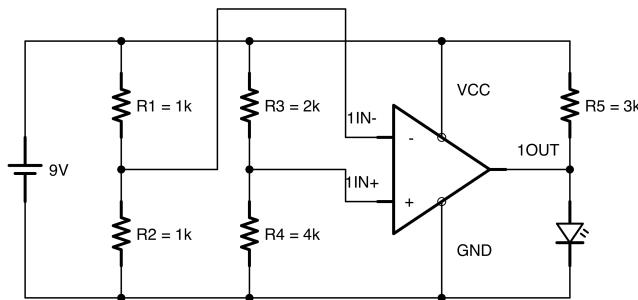
That isn't to say that the datasheets aren't important, but for a beginner the datasheets usually aren't what you need to get started.

11.4 A Simple Circuit with the LM393

In this section, I am going to show a simple circuit using the LM393 chip. In doing so, we are going to be using several of the resistor circuit patterns that we learned in Chapter 9.

The circuit we are discussing is shown in Figure 11.5. Can you identify the resistor circuit patterns? Take a minute and see if you can find some. Note that the wire coming out of $1IN^-$ crosses two wires that it is *not* joined with.

Figure 11.5: A Simple Comparator Circuit



The first thing to notice is that we have *two* voltage dividers. The first voltage divider is between R1 and R2. Since R1 and R2 are the same resistance and are connected to both 9 V and 0 V, that means that they divide the voltage in half, giving a 4.5 V output. The second voltage divider is between R3 and R4. Since R3 is half of the resistance of R4, that means that it only uses up half as much voltage as R4. Thus, since R3 eats up 3 V and R4 eats up 6 V, the wire coming out from the middle is at 6 V.

Then, to the right of the circuit, you can see that we have a current-limiting resistor in front of the LED. That is not its only function, though. It also functions, as we will see shortly, as a pull-up resistor.

So what is the big triangle? Comparators (and several other circuits commonly placed on ICs) are represented as triangles in the schematic (we could have also placed the chip itself there). Each of the connections are labelled the same as they are labelled in the pinout diagram in Figure 11.4 so they would be easy to locate.

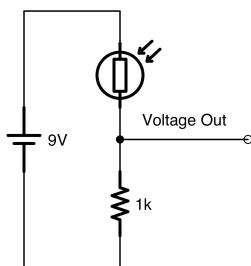
The way that the circuit works is very simple. The voltage coming in to 1IN+ is 6 V and the voltage coming in to 1IN- is 4.5 V. Since 1IN+ is greater than 1IN- then that will turn 1OUT to high (positive voltage). However, remember that we said that 1OUT *does not conduct* when it is high. It acts like an open switch. Therefore, R5 acts like a pull-up resistor and supplies the positive voltage for us to our LED to turn it on.

Now let's say that the input voltages were reversed. What would happen? If 1IN- is greater than 1IN+, then 1OUT will go low (zero volts) and also conduct. It will act like a closed switch going to ground.

Therefore, current will go the easy route - it will go through 1OUT (directly to ground) instead of through the LED (1.8 V or more). This works just like the switch in the circuit in Section 9.4. When 1OUT is low, it acts like a closed switch to ground. When 1OUT is high, it acts like an open switch (and is whatever positive voltage you supply yourself).

The resistor R5 does several jobs. The first job is to act as a pull-up resistor. Remember that a pull-up resistor prevents the load to ground from going too high when the switch is closed. Without the pull-up resistor, when the switch is closed (1OUT goes low), we would have a short-circuit from the voltage source to ground. This would not only waste a large amount of electricity, it would break the LM393, because it can only sink a maximum of 6 mA of current. Having a 3 k Ω resistor, we limit the current for the closed switch to $I = V/R = 9/3,000 = 0.003A = 3\text{mA}$.

Figure 11.6: A Simple Resistor Sensor Circuit



When the switch is open, the current flows through the resistor to the LED, and then the resistor acts as a current-limiting resistor for the LED. The amount of current to the LED will be calculated as $I = V/R = (9 - 1.8)/3,000 = 7.2/3,000 = 0.0024 \text{ A} = 2.4 \text{ mA}$.

11.5 Resistive Sensors and Voltages

One of the more practical uses of the voltage comparator circuit is to measure the values of sensors which act as variable resistors. Many different materials in the world act as resistors. What's really interesting is that many of these materials *change their resistance* depending on external factors. Some of them change their resistance based on temperature, pressure, light, humidity, and any number of other environmental factors.

Now, changing resistance doesn't tell us much by itself. If we put a resistor between a voltage source and ground, it will always eat up that voltage source. However, if you use it in concert with a fixed resistor to make a voltage divider, you can then get the output voltage to vary based on the changes in resistance.

Figure 11.6 illustrates this principle. It is a simple voltage divider, where the top resistor is actually a photoresistor (a resistor that varies based on light) and the bottom resistor has a fixed resistance. Thus, as the light varies, the top resistance will vary. This will change the ratio between the top and bottom resistor, which will affect the output voltage.

To use this circuit, you will need to know the resistances of your photoresistor on the different conditions you are interested in. I usually use the GL5528, which ranges from $10\text{k}\Omega$ in bright light to $1\text{M}\Omega$ in complete darkness. However, depending on your specific photoresistor as well as the light conditions that you think of as "light" and "dark," the resistance values that are relevant for light and dark will be different for you. So, whatever photoresistor you use, it is worthwhile to measure the resistance using your multimeter in the different conditions you think of as light and dark.

11.6 Sensing and Reacting to Darkness

So far in the book, we have focused entirely on example circuits that didn't really do anything. They lit up, they had voltage and current, but there wasn't much interesting that they were doing. However, now, we finally have enough knowledge to start building circuits that *do* something.

We have:

1. A way to generate a fixed voltage (using a voltage divider)
2. A way to generate resistances from real-world events (photoresistors and other resistance sensors)
3. A way to convert changes in resistances to changes in voltage (using a voltage divider with one fixed resistor)
4. A way to compare our varying voltage to our fixed voltage (using the LM393 comparator)
5. A way to utilize the output signal from the LM393 to do work (using the pull-up resistor and the LED)

There are a lot of pieces to put together this simple circuit, which is why it has taken so long to do anything worthwhile. However, if you have followed along carefully, now that you are here you should be able to see how all of this fits together.

What we will do is to take the circuit given in Figure 11.5 and modify R4 to be our photoresistor and R3 to be a fixed resistor. In my own testing, I discovered that the light/dark switchover point for my photoresistor was about $15\text{ k}\Omega$. Therefore, I am going to use a $15\text{ k}\Omega$ resistor as the fixed resistor for R3. Yours may need to vary based on your experimentation with your photoresistor.

When the light is on, my photoresistor will have a lower resistance than $15\text{ k}\Omega$, which will make the fixed resistor R3 use up more of the voltage. Thus, the voltage at the divider will be less than 4.5 V, which will turn 10UT to low (which closes the switch and makes a path to ground on the output before it gets to the LED, which turns the LED off).

In low-light conditions, the resistance will jump way up above the resistance of the fixed resistor. If the upper, fixed resistor has less resistance than the bottom resistor, then the voltage at the divider will be larger than 4.5 V, activating the comparator and turning 10UT to high (i.e., opening the switch and allowing power to flow through the LED).

The final circuit is given in Figure 11.7. You can see a way to lay it out on the breadboard in Figure 11.8.

11.7 Sources and Sinks

Two terms that often come up when dealing with circuits are the concepts of a current **source** and a current **sink**. A source is a component whose pins might provide current to other parts of the circuit. A sink is a component whose pins might pull current from other parts of the circuit.

Figure 11.7: Darkness Sensor Schematic

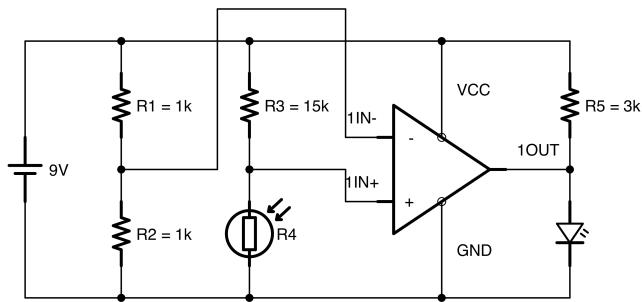
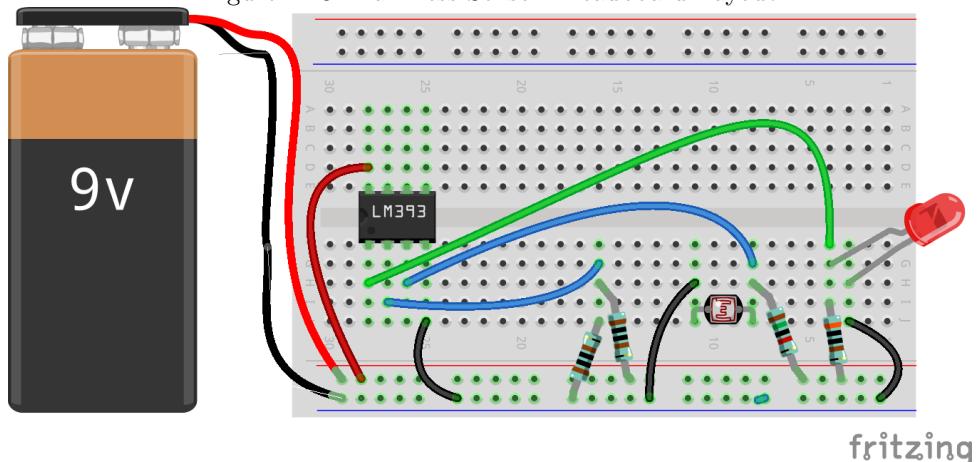


Figure 11.8: Darkness Sensor Breadboard Layout



For the LM393, its input pins neither source nor sink current (at least not any significant amount). The input pins more-or-less just sense the voltage without pulling any measurable current. Therefore, they are neither sources nor sinks of current. Technically, they probably sink a few nanoamps (billions of an amp), but not nearly enough to affect our circuit analysis.

The output pin, even though it is called an *output*, doesn't source any current. Instead, it acts either as a sink (when low) or as a disconnected circuit (when high). This is known as an **open collector** output.

Anytime an IC sources or sinks current, be sure to read the datasheets on the maximum amount of current it can source or sink. These are usually quantities that *you* have to limit—they are merely telling you at what point their circuit will physically break. Therefore, you must use resistors to limit the currents to make sure that they are within limits.

However, be aware that many (but certainly not all) ICs do not source current, using open collectors for their output operations. This has the disadvantage that you have to supply your own voltage and pull-up resistor to the output pin, but it also has the advantage that the output is set to *whatever voltage level you choose*. In other words, you don't need to pick a new comparator IC to get a different output voltage.

Review

In this chapter, we learned:

1. Integrated Circuits (called ICs or chips) are miniaturized circuits packaged up into a single chip that can be added to other circuits.
2. ICs can have a few or several billion components on them, depending on the function.
3. ICs have different types of packages, including through-hole (optimized for breadboards) and surface mount (optimized for soldering and machine placement).
4. Dual In-line Packages (DIP) are the most common through-hole packaging type used for students, hobbyists, and prototype-builders.
5. DIP chips should be placed in the breadboard saddling the bridge, so that each IC pin is attached to its own terminal strip.
6. On most chips, pin 1 is located immediately counterclockwise of the notch in the chip, and remaining pins are numbered counterclockwise.
7. Most ICs are active devices, meaning that they have a direct connection to a power supply in addition to their input and output pins.a
8. An IC's Datasheet is a document that tells about the electrical characteristics of an IC. However, most of them are difficult to read and assume you are already familiar with the part. However, they are very useful for getting a pinout for the chip as well as telling the maximum ratings for voltages and currents.
9. The LM393 is a dual voltage comparator IC—it compares two voltages and alters its output based on which is larger.
10. The LM393's inputs do not consume any significant current on them when sensing the input voltages.
11. The LM393's outputs are open collectors—which means that they act as a switch to ground. When the output is “low” the pin acts as a closed switch to ground. When the output is “high” the pin acts as a disconnected circuit.
12. Because the LM393 acts as a disconnected circuit when high, a pull-up resistor circuit is required to get an output voltage.
13. Many sensors are based on the fact that the resistance of many materials will change with environmental factors. Therefore, the sensor acts as a variable resistor, with the resistance telling you about the environment.
14. A resistive sensor can be used with a fixed resistor to make a variable voltage divider, essentially converting the resistance to a voltage.
15. By putting the resistive voltage divider in comparison with a fixed reference, we can use the LM393 comparator to trigger an output when the sensor crosses some threshold of resistance.

Apply What You Have Learned

1. Calculate the amount of current flowing through each element of the circuit in Figure 11.5. You can presume that the LM393 uses about 1 mA for its own operation, and that the LED is a red, 1.8 V LED. What is the total amount of current used by the circuit?
2. Take the circuit in Figure 11.5 and swap which voltage divider is attached to 1IN+ and 1IN-. Now calculate the total amount of current used by this circuit.
3. The Spectra Flex Sensor is a resistive sensor that changes its resistance when bent. When it is straight, it has a resistance of $10\text{ k}\Omega$. When it is bent, it has resistances of $60\text{ k}\Omega$ and above. Draw a circuit that turns on an LED when the resistor is bent. You may invent your own symbol for the flex sensor.
4. Build the circuit in Figures 11.7 and 11.8.
5. If you wanted to wait until the room was even darker before the LED went on, how would you change the circuit?

Chapter 12

Using Logic ICs

In Chapter 11, we worked with our first Integrated Circuit, the LM393 Voltage Comparator. In this chapter, we are going to look at other ICs and talk more about how they are named and used in electronics.

12.1 Logic ICs

One of the easiest class of ICs to use are the *logic* ICs. A logic IC is a chip that implements a basic function of **digital logic**. In digital logic, electric voltages are given meanings of either “true” or “false,” usually with “false” being a voltage near zero, and “true” being a positive voltage (often between 3–5 volts). These values are also referred to as 1 (for true) and 0 (for false), or HIGH (for true) and LOW (for false). Then, the digital logic ICs implement logic functions that combine different signals (usually designated as A and B) and give an output signal (usually designated as Y or Q).

For instance, the **AND** function will output a “true” (positive voltage) value if both of its inputs are true, and will output a “false” (near-zero voltage) value otherwise. In other words, if A *and* B are true, Y is true. As another example, the **OR** function will output a “true” value if either of its inputs are true. In other words, if A *or* B are true, Y is true. Figure 12.1 shows the most common types of logic operations and how they work.

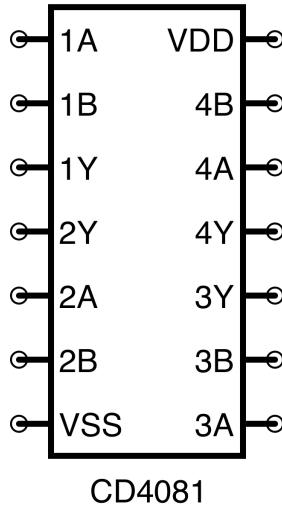
As we have seen, AND yields a true result when both A and B are true and OR yields a true result when either A or B are true. So what are the others? **XOR** is *exclusive OR*, which means that it is just like OR, but is also false when both inputs are true. **NOR** is *not OR*, which means that it is the exact opposite of OR. Likewise, **NAND** is *not AND*, which means that it is the exact opposite of AND. Finally, **NOT** only has one input, and simply reverses its value.

Each digital logic function, when implemented in electronics is called a **gate**. The nice thing about building circuits with logic gates is that, rather than using math, you can build circuits based on ordinary language. If you were to say, “I want my circuit to output a signal if both button 1 *and* button 2 are pressed,” then it

Figure 12.1: Common Logic Operations

Operation	A	B	Y (output)
AND	false	false	false
AND	false	true	false
AND	true	false	false
AND	true	true	true
OR	false	false	false
OR	false	true	true
OR	true	false	true
OR	true	true	true
XOR	false	false	false
XOR	false	true	true
XOR	true	false	true
XOR	true	true	false
NOR	false	false	true
NOR	false	true	false
NOR	true	false	false
NOR	true	true	false
NAND	false	false	true
NAND	false	true	true
NAND	true	false	true
NAND	true	true	false
NOT	false	N/A	true
NOT	true	N/A	false

Figure 12.2: The Pinout of a CD4081 Chip



is obvious that you would use an AND gate to accomplish this.

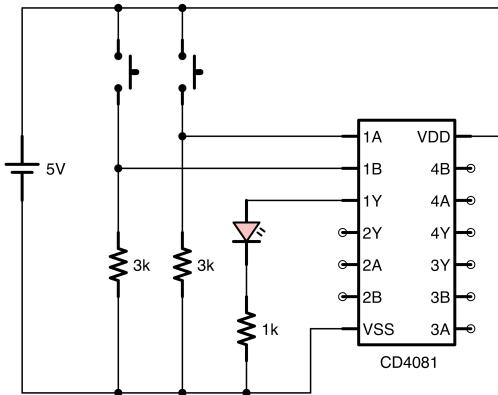
Most logic gates are implemented in chips that contain multiple (often four) implementations of the same gate. For instance, the CD4081 chip is a quad NAND gate chip. The pinout for this chip is shown in Figure 12.2 Note that it has a supply voltage pin (pin 14) as well as a ground pin (pin 7) to supply power to all the gates on the chip. Each logic gate is numbered 1–4 and the inputs are labelled A and B with the output of Y.

To use the chip, you pick which one of the four gates you are going to use (it doesn't really matter which). If we want to use Gate 1, then we put our inputs on 1A and 1B and then our output signal goes to 1Y. Note that, unlike the IC from the last chapter, this logic gate has a powered output—it actually supplies voltage and current to drive a (small) output signal.

Logic gates are wired to expect relatively fixed, predefined voltages on their inputs, and output the same voltage levels. They do not need current-limiting resistors for their inputs because the inputs themselves are usually high-resistance (i.e., $1,000,000 - 10,000,000 \Omega$). Because of the high resistance on the inputs, it also means that even if there is a resistor on the input, it will not affect the input voltage significantly (think of a voltage divider with $1,000 \Omega$ for the first resistor and $10,000,000 \Omega$ for the second resistor—the voltage will not change much after the first resistor). It also means that the current going into the gate is essentially ignorable ($I = \frac{V}{R} = \frac{5}{10,000,000} = 0.0005 \text{ mA}$).

For some logic chips, the input voltage is expected to be around 3.3 V or 5 V, while as for others it is based on the supply voltage. However, nearly all ICs are limited in how much current they can put out before they fry. This is usually somewhere in the range of 8 – 20 mA, depending on the chip. Because of this, if you use

Figure 12.3: Example Circuit Using an AND Gate



a logic gate to directly power a device (such as an LED), you probably will need a current limiting resistor to keep the output current down below these limits.

There are logic chips that have open collector outputs (like the LM393 from Chapter 11), but they are more rare because they are harder to use.

Lets say that we want to build a circuit which will turn on an LED if *both* of two buttons are pushed at the same time. Figure 12.3 shows a circuit to accomplish this. It has two buttons, one wired to 1A (pin 1) and one wired to 1B (pin 2). The output 1Y (pin 3) then goes to an LED with a current limiting resistor. You may wonder what the resistors attached to the buttons are doing. Those will be explained in Section 12.3.

For most logic chips, the manufacturers recommend that unused inputs (but not outputs!) be connected to ground. This makes the chip more efficient in power consumption, but for simple projects like these it isn't really necessary. If you wish to connect the unused inputs to ground then it is a better circuit design.

Note that the circuit shows a 5 V source. While the CD4081 is tolerant of a wide range of input voltages and would operate just fine at 9 V, many digital logic chips are not. Many digital logic chips operate at pre-specified voltages, usually either 5 V or 3.3 V. Therefore, we will take a moment and look at how we can get an input source for a specific voltage.

12.2 Getting a 5 V Source

So far in this book, however, we have mostly dealt with 9 V batteries. However, digital logic circuits often operate at lower voltages (usually 5 V or 3 V).

Therefore, we need to find a way to convert a 9 V source into a 5 V source. There are several options for doing this, all depending on your requirements and/or the supplies you have available to you.

Figure 12.4: A 7805 Voltage Regulator in a To-220 Package

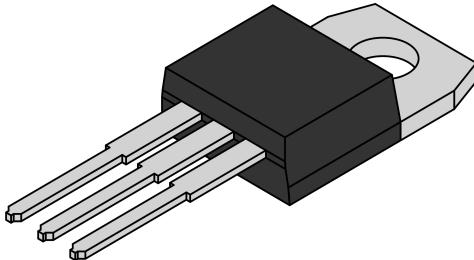
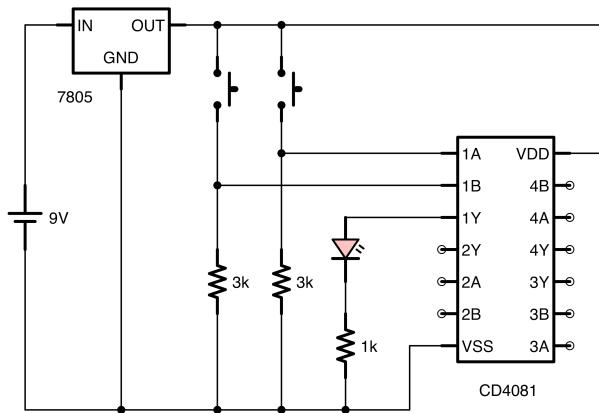


Figure 12.5: Logic Gate Circuit with a Voltage Regulator

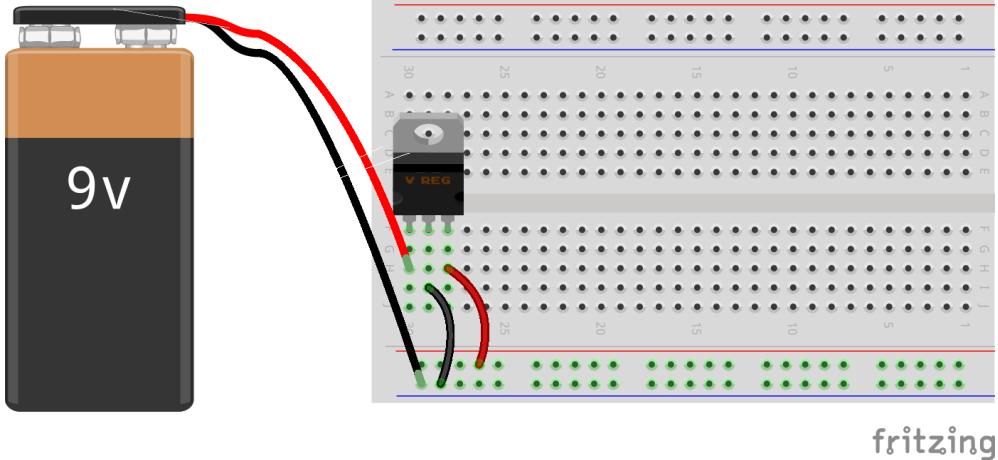


One option is to build a simple 5 V power supply using the knowledge you already have. In Chapter 9 we showed how to build a voltage divider to step down the voltage from a higher voltage source to a lower one. Although not ideal, this could work fine for simple test circuits. A better option would be to build the Zener diode voltage regulator that was shown in Chapter 8 if you have a 5 V Zener diode handy.

Another option is to use a voltage regulator IC. The LM7805 is a simple voltage regulator circuit you can use to convert a 9 V voltage source (or higher—up to 24 V) into a 5 V voltage source with minimal current loss. It is itself an IC, though with a different kind of packaging than we've seen, known as a **TO-220 package**. You can see what this looks like in Figure 12.4. On these packages, if you are reading the writing on the package, pin 1 (input voltage) is on the left, pin 2 (ground) is in the middle, and pin 3 (output voltage) is on the right. Figure 12.5 shows what this looks like in a circuit diagram.

Figure 12.6 shows how to attach the LM7805 regulator to your breadboard. First, plug the regulator into your breadboard so that each pin is on its own terminal strip. Next, plug the positive wire from the battery into the terminal strip with the voltage regulator's pin 1 and the negative wire from the battery to the negative/ground power rail on the breadboard. Then, connect the voltage regulator's pin 2 (ground) to the negative/ground power rail. Finally, connect the voltage regulator's pin 3 (output voltage) to the positive

Figure 12.6: Simple Way to Attach the LM7805 to Your Breadboard



power rail. You now have a 5 V supply!

Note that some LM7805s have pins that are too big for breadboards. That's unfortunate, but they are pretty rare. As long as you buy from companies that target hobbyists, you are likely to get a component that will work well with breadboards.

Another option for 5 V power is to use an add-on unit for your breadboard. There are many full-featured power units available for use in standard breadboards (unfortunately, there is no standard name or part number for these units, so we will just call them *breadboard power units*). This type of unit plugs into the power rails of your breadboard, and can output either 5 V (the logic voltage we are using here) or 3.3 V (another popular logic voltage). The breadboard power unit can take voltage from a variety of sources, including batteries (with a compatible plug), a wall outlet (with an appropriate adapter), or even with USB power (either from your computer or a wall charger). To use the breadboard power unit, be sure the jumpers are set to the correct output voltage, and be sure to plug it in to your breadboard in the correct direction. There is also an on/off switch provided in most such units so that you don't have to wire one yourself. The breadboard power unit has positive/negative markings, so be sure they line up with the positive/negative markings on your breadboard.

FIXME—Show a photo of the power unit

For the rest of the book, if the schematic requests a voltage other than 9 V, feel free to use any of these methods to supply the proper power to your projects.

12.3 Pull-Down Resistors

In Figure 12.3, we looked at the circuit diagram for a simple AND gate. We noted that each button had a resistor connecting it to ground, but we did not mention why. In digital logic circuits, buttons and single-pole

switches, when they are open, essentially disconnect the circuit. Because the inputs are high-resistance inputs (i.e., they use very little current), simply disconnecting the input circuits is not always enough to turn them off! Think of it this way—when you connect the circuit by pushing the button, the whole wire becomes positive. When you let go of the button, the state of the wire has not changed. Eventually the positive charge will drain out through the gate, but, since the input uses so little current, it will take a while for that to happen. Therefore, we have to provide another path for the electricity to go when the button is not pressed. Note that some logic chips actually supply pull-up resistors internally which make the inputs always positive when disconnected. In those cases, the pull-down resistor does essentially the same job, but is even more necessary than before.

These resistors are called pull-down resistors because, when the button circuit is not connected, they pull the voltage level down close to zero through the resistor. The resistor is very important because, when the button is connected, it keeps the voltage high and limits the amount of current that leaks out across the resistor. If you directly connected the button to ground without the resistor, then pushing the button would not raise the voltage because it is still directly connected to ground, and would therefore remain at zero volts. Having the resistor there makes sure that the voltage on the inputs remains high while the button is pressed, and bleeds off when the button is released.

In short, without a path to ground, when you let go of the button, the input could remain high. However, without the resistor, pushing the button would cause a short-circuit. Therefore, a pull-down resistor allows voltage to drain off quickly when the button is not pressed, but also prevents disasters and wasted current when the button is pressed.

The value of a pull-down resistor is usually somewhere between $1\text{ k}\Omega$ and $10\text{ k}\Omega$. Beyond $10\text{ k}\Omega$ the actual function of pulling the voltage down to zero can be slowed down. Additionally, even above $4\text{ k}\Omega$ it is possible to interfere with the actual logic operation of the chip. Having a resistor below $1\text{ k}\Omega$, however, means that you are just wasting current.

So, for any button-type input to a digital logic circuit (where the circuit is *physically disconnected* when the input is off), a pull-down resistor is needed to make sure that the input *actually* goes low when the circuit disconnects.

12.4 Combining Logic Circuits

Logic chips that operate at the same voltage are very easy to combine together. Let's say that you had three buttons that you wanted to monitor, and you wanted the light to come on if someone pushed either buttons 1 *and* 2 together *or* button 3 (or all of them). To do that, you would need an AND gate and an OR gate. Buttons 1 and 2 would be wired with the AND gate, and button 3 would be combined with the output of the AND gate through an OR gate.

Figure 12.7 shows what this looks like. Since there are so many voltage/ground connections, the figure does not have an explicit battery drawn, instead it simply shows +5 V wherever it should connect to the voltage source, and a ground symbol wherever it should connect to the battery negative. As you can see here, there are two logic ICs—the CD4081 having the AND gate and the CD4071 having the OR gate. The output of the first AND gate is wired into one of the inputs of the OR gate.

Figure 12.7: Multiple Logic Gates Combined in a Circuit

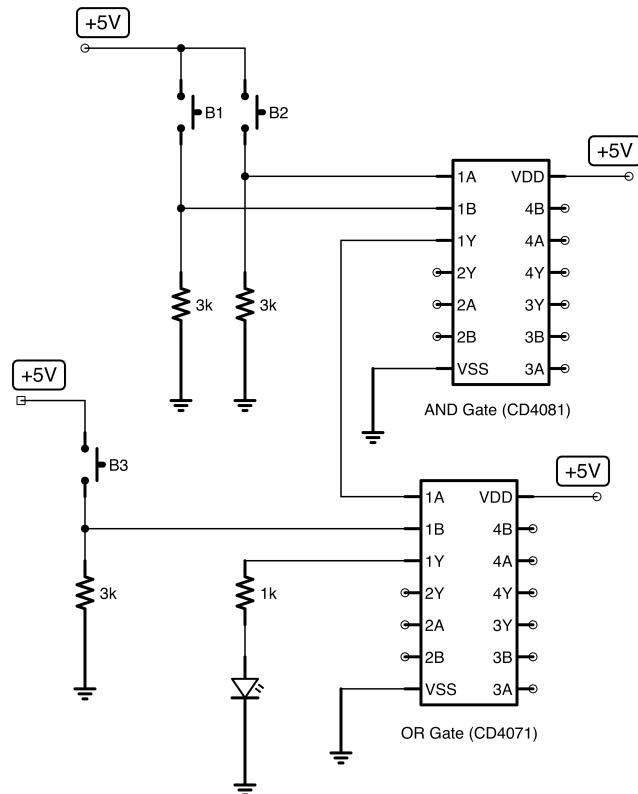
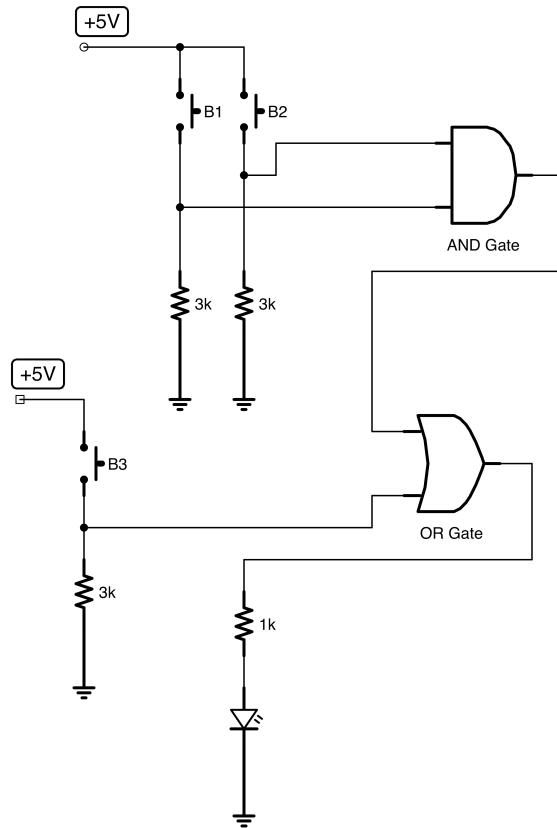


Figure 12.8: Logic Gates Represented as Shapes Instead of IC Pins



This works because, unlike the LM393 (discussed in Chapter 11), these logic gates actually supply output voltage and current as well. Because the inputs to the logic gates are high-resistance, there is no need for a current-limiting resistor when combining gates in this way.

Now, it is fine to draw logic circuits the way we have in Figure 12.7. However, as the logic becomes more complex, actually drawing all of the connections to voltage and ground become tiring, and trying to get all of the wires to the right spot on the chip can get messy as well. Because of this, engineers have devised a simpler way of describing logic gates and logic circuits.

Instead of representing the entire chip on a schematic, engineers will represent only the logic gates themselves. Additionally, since the power goes to the whole chip (and not the individual gates), in such a drawing the power connections for the gates are not shown. The standard that was developed represents each type of gate with a shape. Figure 12.8 shows what this circuit drawing looks like if it is drawn using shaped gates instead of IC pins. The actual physical circuit is the same, this is only to simplify the schematics to make them easier to understand and follow.

Figure 12.9: Common Gates Used in Schematic Drawings

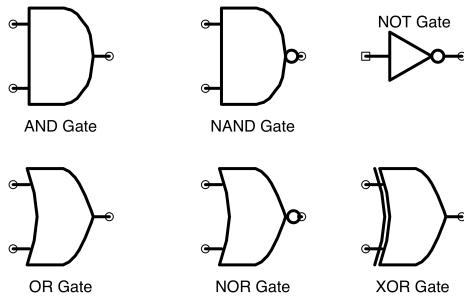


Figure 12.9 shows what these gate drawings look like. The AND gate has a flat back panel and a simple, rounded front. The OR gate looks a bit like a space shuttle, with both the back and the front angled. The NOT gate is a triangle with a circle at the tip. This circle can also be added to other gates to show that the gate is the opposite one. For instance, a NAND gate is drawn by first drawing an AND gate, and then adding a circle to the front, indicating that the gate behaves like an AND gate with a NOT gate in front of it. Similarly, the NOR gate is an OR gate with a circle in front of it. The XOR gate is similar to the OR gate, but with an extra line going across its inputs.

Many times, the internal schematics of a chip are shown using gate symbols, in order to help you understand the operation of the chip and how the pins work. For instance, Figure 12.10 shows how the CD4081 chip is wired up internally. You can see the inputs going through the logic gate, and out towards the output. While this isn't any new information you didn't already know, it may help you understand why the pins are laid out the way that they are.

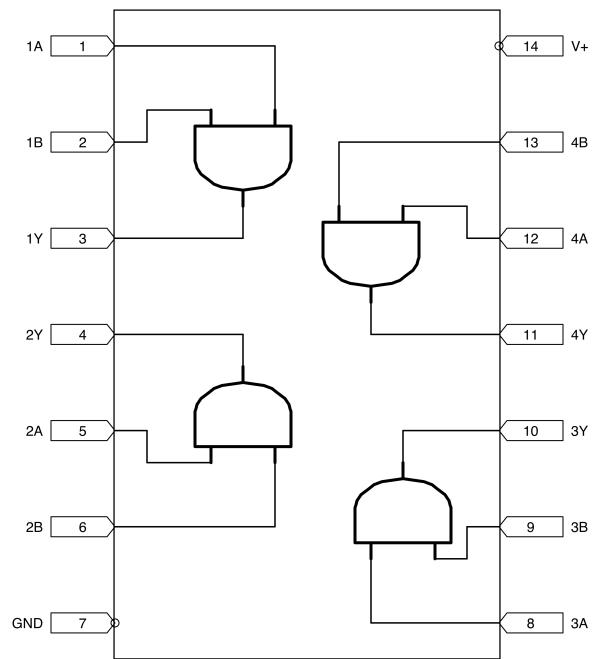
As an interesting side-note, every logic function can actually be built from NAND gates, though you have to wire them up in strange ways. You can actually build a computer entirely from NAND gates if you wanted to. It is not incredibly important, but Figure 12.11 shows how to build each type of logic gate from NAND gates. As an activity, go through the truth tables in Figure 12.1 and see if you can follow how each set of values becomes the result.

12.5 Understanding Chip Names

One of the biggest problems in learning to build electronic devices is the bewildering array of chips, each with some weird name. “Oh, for that you want an NE555P,” or, “You could use a SN74HC00P or a CD4011BE for that task.” What language are such people speaking?

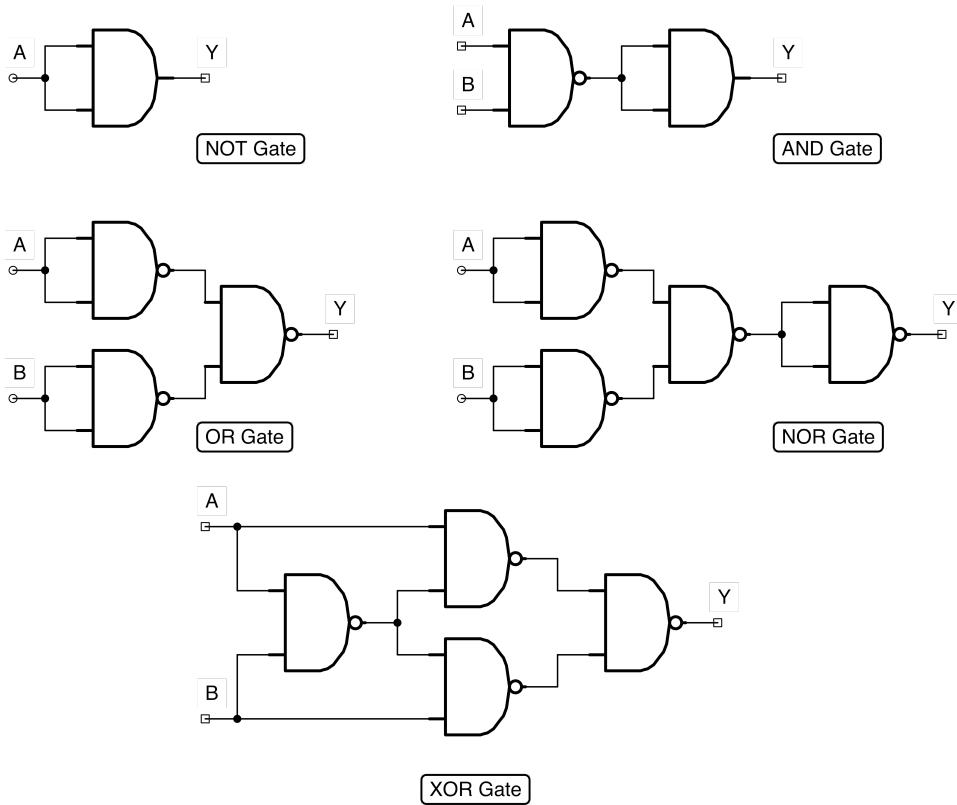
There is a huge selection of chips available, and learning their names is a daunting task. Appendix E attempts to offer some method to the madness, but, at the end of the day, chip names are like people’s names—you get to know them by using them. Nobody knows everybody’s name, but, for the types of projects you like to work on (whatever that happens to be), there will be standard chips whose names you will eventually come to know.

Figure 12.10: The Internal Layout of the CD4081



Once you make it through this book, you should have a solid enough background to search for the chips you need, have some understanding of the part names, and be able to find the chips you need for your projects. If you buy the chips from a seller geared towards amateurs and hobbyists, they will likely also include tutorials and additional information available in an easier-to-understand format than just datasheets.

Figure 12.11: How Each Gate Can Be Built from NAND Gates



Review

In this chapter, we learned:

1. A logic IC implements basic digital logic functions such as AND, OR, NOT, etc.
2. These logic functions refer to essentially the same ideas that they mean in ordinary language, and exactly what they mean in formal logic.
3. Logic ICs use different voltage levels for true and false—usually with true being near the supply voltage and false being near zero voltage.
4. True is sometimes referred to as HIGH or 1. False is sometimes referred to as LOW or 0.
5. The inputs of a logic function are usually designated as A and B, and the output is usually designated as Y or Q.
6. A single digital logic function is called a gate. Most logic ICs have more than one gate on a single chip.
7. Logic ICs require a supply voltage and a ground connection to power the logic.
8. Most logic ICs provide powered logic outputs, so that a “true” value supplies both voltage and a small amount of current on its output. However, a current-limiting resistor is usually required.
9. If an input to a logic IC may be disconnected for its “false” state (as is common with button inputs), then it needs a pull-down resistor to connect it to ground when the button is not being pushed.
10. Logic ICs can usually be combined by wiring the output of one to the input of another to create more complex logical conditions.
11. Logic gates are often drawn in schematics using basic shapes to indicate their operation, rather than as connections to chips. In these cases, the power connections are not shown by schematics.
12. Every logic gate can actually be built from NAND gates wired together.
13. IC names are very confusing and take time and experience to get to know them well.
14. Many ICs require specific voltage levels to operate, often at 5 V or 3.3 V.
15. Many solutions are available for generating specific voltages, including voltage dividers, zener diodes, voltage regulators, and add-on breadboard power units.
16. The LM7805 is a very common 5 V voltage regulator.

Apply What You Have Learned

1. Draw the circuit in Figure 12.3 yourself. Identify the function of each resistor.
2. Build the circuit in Figure 12.3 (don’t forget that the power source should be 5 V).

3. If you assume that no current flows through the inputs of the AND gate, and that the output functions as a 5 V power source, how much current flows through each resistor when all of the buttons are pressed? What, then, is the total current used by the circuit if you ignore the logic gate?
4. Measure the actual current that flows through each resistor. If you are having trouble pushing the buttons while you measure the current, just replace the buttons with wires for this test.
5. Measure the current that it used by the AND gate itself. You can do this by measuring the supply current of the AND gate. Measure it both when its output is true and false.
6. Draw a schematic of a circuit that has two buttons (B1 and B2) which light up an LED if either button is pressed.
7. Draw a schematic of a circuit that has two buttons (B1 and B2) which light up an LED if neither button is pressed.
8. Draw a schematic of a circuit that has four buttons (B1–B4) which light up an LED if either B1 and B2 are pressed or if B3 and B4 are pressed.
9. Look at the construction of the different gates from NAND gates in Figure 12.11. Copy down the OR gate construction four times, and trace how the output is generated for each possible set of inputs (true/true, true/false, false/true, false/false). Show the inputs and outputs on each NAND gate. Compare the outputs to the truth table for the OR function in Figure 12.1.
10. Take the circuit in Figure 12.3 and draw a schematic to use pull-up resistors on the inputs rather than pull-down resistors. How will this change the behavior of the circuit?
11. Let's say that we want to create a door buzzer so that someone outside a door can push a button to be let in. However, the person inside also wants a switch to be able to disable the buzzer. The buzzer can be thought of as a simple device that buzzes when any positive voltage is applied. Draw a circuit diagram of this setup using logic gates. The buzzer can be drawn as a resistor labelled "buzzer" (don't forget to connect the other side to ground).

Chapter 13

Using Logic Chips to Store Values

Chapter 14

Common Integrated Circuits

In Chapter 12 we studied basic logic circuits. This chapter will introduce you to a few more complex integrated circuits that are generally useful in a variety of applications. Even more types of ICs can be found in Appendix ??.

14.1 Holding a State

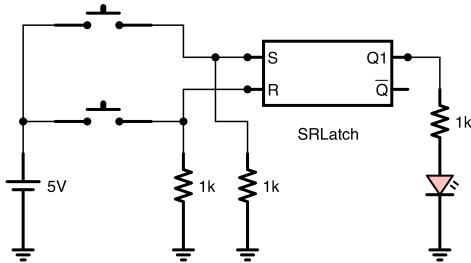
Up until now, all of our circuits have fluctuated with their inputs. That is, the output is always determined by the *present* state of the inputs. But what happens if we want a circuit to *remember* that something happened? For that, we will need a way to set a state in the circuit and then hold it. That is, we need something that we can tell it to remember a true/false value until we tell it not to.

Holding on to past states is called **memory**. In your computer you have huge memory chips that have billions of switches that can hold a state. For our purposes, we will content ourselves to using chips that only hold a few states.

The simplest kind of memory in electronics is known as a **latch**. Latches hold a single **bit** of memory. A bit is simply a single true/false signal (i.e., positive voltage/zero voltage). Latches allow you to store a true/false value and continue to retrieve it as often as you want until you choose to reset the value. There are many different latches that are based on how they are set (and how complicated the circuitry is to implement them).

The easiest type of latch to learn about and use is the **SR Latch**. The SR Latch holds a value that it continually outputs on its Q pin. Additionally, some latches have an additional output which outputs the opposite of the Q pin, known as \bar{Q} . The SR Latch has two inputs—set (S) and reset (R). When the set (S) input alone is true, Q gets set to true. When the reset (R) input alone is true, then Q gets reset back to false. If both S and R are false, then, the latch continues to hold its previous state. This allows for both very easily setting a state, as well as a very easy implementation.

Figure 14.1: Simple Circuit Using an SR Latch



Unfortunately, most latches start out in an *unknown* state when they are first powered on. This means that if you need it to be in a particular state when it turns on, *you* have to provide circuitry to give the latch its starting value. For the circuits in this book, we will not be overly concerned with the starting value of the latch.

To see the latch in action, Figure 14.1 shows a simple circuit using an SR Latch. Notice that both button inputs have pull-down resistors going to ground in order to be sure that the inputs always have a valid state. When the upper button is pressed, then the latch sets Q to true and holds it, even after the button is no longer pressed. When the lower button is pressed, the latch resets Q to false and holds it, even after the button is no longer pressed. Note that in a real circuit, the SR Latch would also need to be powered as well.

The CD4043 chip is a quad SR Latch integrated circuit and can be used to build the project. Figure 14.2 shows how to connect the circuit. It is just like the circuit in Figure 14.1, except that we are also showing the connections for the supply voltage. Additionally, there is a pin labelled “ENABLED” that we are connecting to the power supply. On many chips, you have to specifically connect certain pins to ground or to the supply voltage to get them to work like you want them to. On this chip, it has a feature that allows you to connect or disconnect all of the outputs using the ENABLED pin (when they are disconnected, they act like there is no circuit there at all—neither true nor false). We always want our outputs connected, so we just attach the ENABLED pin to the supply voltage.

Interestingly, SR Latches are fairly easy to implement using the standard gates discussed in Chapter 12. Figure 14.3 shows how this is done. It is simply two NOR gates wired so that their outputs feed into one another.

To understand how this works, think about what happens when S is true and R is false. Since the S is on a NOR gate, the output of the NOR gate will go to false. This provides the output signal \bar{Q} as well as one of the inputs to the top NOR gate. As long as the R stays at false, the output of the top NOR gate will always stay true, since neither input is true. This “true” output then becomes Q , as well as the input to the bottom NOR gate, which keeps it on even when the S input goes to false. It isn’t critically important to understand how this latch works, but sometimes knowing how something works can help you solve similar problems, or even just have a deeper intuition about how these work.

There are several other types of latches as well. An $\bar{S}\bar{R}$ Latch is just like the SR latch except that the inputs are inverted. A JK Latch is similar to an SR Latch, except that S is renamed J , R is renamed K , and the

Figure 14.2: An SR Latch Circuit Implemented Using a CD4043

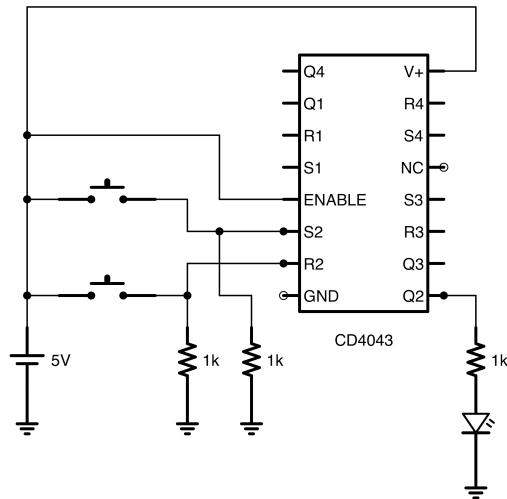
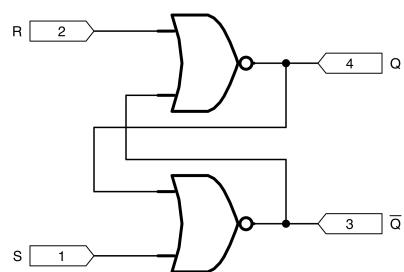


Figure 14.3: An Implementation of an SR Latch



latch defines a new behavior if *both J* and *K* are true (the SR Latch usually doesn't define what happens in this case). A D Latch is a little bit of a different beast. It has an Enable (*E*) pin and a data (*D*) pin. When the *E* pin is true, then whatever is in the *D* pin becomes *Q*. When the *E* pin goes false, then whatever was the last state of *Q* stays put there, no matter what *D* does. It remains in that state until *E* goes positive to allow *D* to influence *Q* again.

A flip-flop is similar to a latch, except that it uses an external clock pulse to synchronize changes between states at given intervals. We will not discuss clocked chips here.

Part III

Microcontrollers

Chapter 15

Introduction to Microcontrollers

In Chapter 12, we learned the basics of digital logic. However, I think we can all agree that those chips wound up taking up a lot of space on our breadboard. If we wanted to do a lot of complicated tasks, we would wind up needing a lot of chips, and our breadboard would get unwieldy very quickly. Additionally, as the number of chips increased, it would get very expensive to build such projects.

Additionally, when all of the logic of a circuit is hardwired into the circuit through logic chips, it is very difficult to change. If you need to add buttons, or remove buttons, or do anything else, you wind up needing to wade through masses of circuitry to make the change you want. Then, if you are mass-producing the circuit, you have to setup for mass production all over again.

To solve all of these problems (and more), the microcontroller was introduced. A microcontroller is essentially a low-power, single-chip computer. A “real” computer chip usually relies on a whole slew of other chips (memory chips, input/output chips, etc.) to operate. A microcontroller contains all of these (though usually on a smaller scale) in a single chip that can be added to an electronics project.

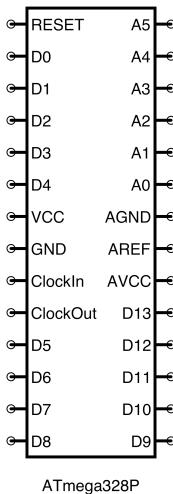
Unlike your typical computer, most microcontrollers can’t be connected to a keyboard or other typical input, and can’t be connected to a monitor, disk drive, or other typical output. Instead, microcontrollers usually communicate entirely through digital (true/false) electrical signals on their pins.

So, instead of wiring complex logic onto their boards, many people opt to have microcontrollers provide the bulk of their digital logic. One complication that this adds, however, is that, since the microcontroller is essentially a computer, then just like a computer, it has to be programmed. This means that not only must circuit designers be familiar with electronics, they must also be familiar with computer programming.

15.1 The ATmega328/P Chip

The microcontroller we will be focusing on is the ATmega328/P. Actually, we will focus less on this specific chip than the overall environment surrounding it, known as Arduino. However, it is good to have a quick

Figure 15.1: A Simplified Pinout of the ATmega328/P



introduction to this chip and how it works.

The ATmega328/P is part of a family of microcontrollers developed by Atmel known as the AVR family. The AVR became popular because it was one of the first chips to use flash memory to store its programs, which allowed the onboard programs to be more easily changed.

Figure 15.1 shows a simplified pin configuration of the chip, focused on how it is used in the Arduino environment. The VCC pin and the GND pins are the primary power pins. The chip can run on a range of voltages, but 5 V is a very common and safe setting. AVCC and AGND power the chip's analog-to-digital converter unit.

All of the pins labelled “D” are digital input/output pins. They can be configured as inputs for buttons or other signals, or as outputs for driving LEDs or other output devices. The pins labelled “A” are analog input pins. While the digital input pins can only read that a value is true/false, the analog pins can read voltages and convert them to numbers. AREF is a “reference voltage” used for setting the maximum voltage for analog inputs, but is usually unconnected (it should also not be higher than AVCC).

Microcontrollers, like most processors, control their operation by using a “clock.” This is not a clock like you normally think of. A better way to think of this is as a heartbeat. Basically, there is a continuous signal of pulses that are provided through the clock, and the pulses allow the chip to synchronize all of its activities. The ATmega328/P has an internal clock, but it can also be more efficiently operated by connecting an external clock (quartz crystals, for instance, provide a *very* steady pulse).

You might wonder, what does the chip *do* with its input and output pins? That is entirely up to you. It does *whatever you program it to do*. The ATmega328/P has **flash memory** on the chip which can store a computer program (flash memory means that it will remember the program even after the power turns off). You have to upload your program to the chip, and then after that it will do whatever you like with its

inputs and outputs. The D0 and D1 pins, in addition to providing input and output, can also be used to reprogram the chip. We will learn how to program the chip in Section 15.4.

15.2 The Arduino Environment

The chip itself is just one piece of the puzzle. In order to use the chip, you have to be able to program it. Programming requires the use of programming tools on your main computer. In addition, you also need some way to take the program that you built on your computer and load it onto the chip. That takes both software and hardware.

Then, once the program is on the chip, you have to build a circuit to properly power the chip. This requires voltage regulation for the VCC pin, and several other recommendations from the manufacturer about how to setup the other pins. All of this can be quite a lot of work, and a lot of pieces that need to be brought together.

Thankfully, most chips have what is called a **development board** that can be purchased. A development board is a pre-built circuit that has a microcontroller chip pre-connected in its recommended manner. It is made to simplify the work of developing circuits. Likewise, most chips have a recommended **programming environment** as well. A programming environment is a set of tools for your computer that allow you to create programs for your microcontroller. Additionally, a device called an **in-system programmer** connects your computer to your chip or development board and will transmit the program from your computer to the chip.

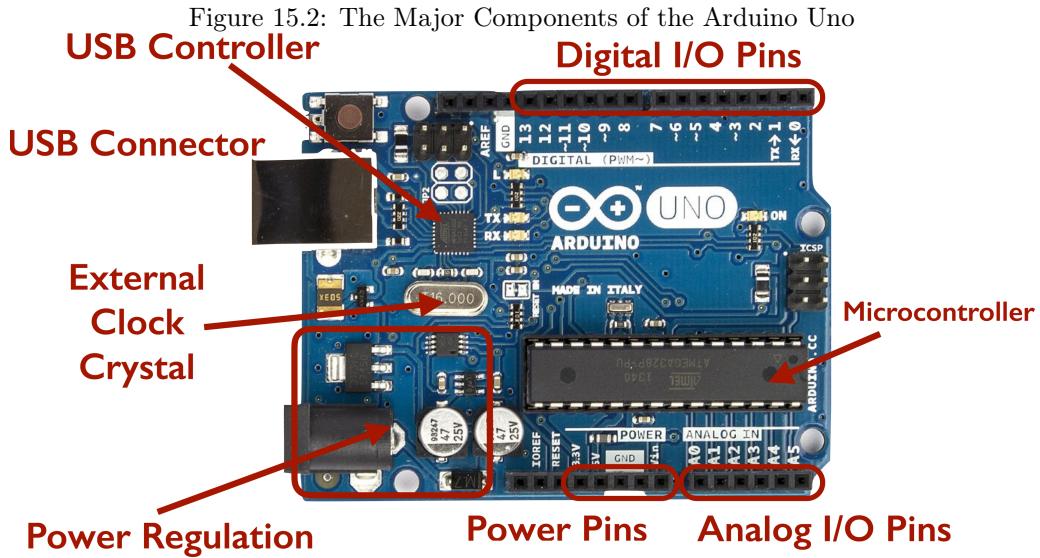
In 2005, a complete, simplified system for doing all of these tasks called **Arduino** was created, based off of an earlier system called Wiring. Arduino consists of (a) a simplified development environment for your computer to write software for microcontrollers, (b) a simplified development board to make it very easy to build electronics projects, and (c) integrating the in-system programmer into the development board so that all that is required is a USB cable.

The Arduino environment supports a number of different microcontroller chips. Because it is a simplified environment, many of the special features of individual chips are not directly supported. However, for getting started and doing basic projects, the Arduino environment is excellent.

Even though there is a company behind Arduino, there are many Arduino-compatible boards made by other manufacturers. These boards use the same ATmega328/P microcontroller, and often have very similar development boards and functions. Most importantly, they are compatible with the programming tools on the Arduino environment.

15.3 The Arduino Uno

This book focuses on the Arduino Uno development board. Figure 15.2 shows what the board looks like, as well as a general idea of what the different areas of the board accomplish. The Uno is very nice because the USB port allows a whole slew of functions—not only can it be used to receive programs for the chip, but you



can also power the board through the USB, as well as send data back-and-forth to the computer through it. If you are not connected to USB, there is a separate power plug that can be plugged into the wall or to a 9 V battery.

The Arduino Uno provides chips for power regulation, USB communication, as well as the ATmega328/P microcontroller itself. It also supplies an external clock for the microcontroller. Finally, it provides **headers** (places on the board to plug in wires) for the major pins on the microcontroller. Thus, everything you need to make use of the chip is provided for you in this development board. You simply connect the input and output pins to your own breadboard and you can have a working project that you can program.

15.4 Programming the Arduino

Now that we have seen the pieces of the Arduino environment, let's tackle programming the Arduino. This book is not a book about programming, so we will only cover the absolute basics.

The programming tool for the Arduino is called the **Arduino IDE**. IDE stands for “Integrated Development Environment”—in other words, the thing that you develop with. The Arduino IDE is available for pretty much any computer—Mac, Windows, or Linux. You can download the IDE from <http://arduino.cc/>.

Depending on whether you purchased an “official” Arduino or a clone, you may also have to download an additional driver for the USB interface. You can download the driver from <http://bplearning.net/drivers>. Once you have installed the Arduino IDE and the USB driver, you are ready to start!

We will begin by using an example program (called a “sketch” in Arduino terminology) that ships with the

Arduino. First, connect your Arduino to your computer with a USB cable. Open up the Arduino IDE, then click “File,” then “Examples,” then “01.Basics,” and finally click on “Blink.” This loads up a ready-made program for your Arduino. This program simply turns the D13 pin on and off. On an Arduino, the D13 pin already has an LED attached to it, so you don’t even need to add any components!

Now that you have the program loaded up, click the button with the checkmark icon. This verifies that the program is written in a way that the computer can understand. If it has any errors, it will show them in the black panel on the bottom.

Now you need to make sure that the IDE is targetted at your board. Go to “Tools” and then “Board” and make sure that “Arduino/Genuino Uno” is selected. Then, click on “Tools” and then “Port” and make sure your Arduino was detected and that it is selected. If you don’t see your Arduino listed here, you may need to check the USB driver installation.

Once your configuration is verified, click the button with the arrow icon to upload it to the Arduino. It should take about 2–5 seconds, and then the LED on your Arduino should start blinking. If there are any errors, they will display in the black status area below. Note that some Arduinos come with this program pre-installed. If this is the case, your Arduino may not have changed what it is doing much. You can verify that it is all working by changing the program slightly. If you change all of the numbers that say 1000 to 500 it should blink twice as fast. Remember, though, that you must verify it (click the checkmark button) and upload it (click the arrow button) to get your new code onto the board.

Now, let’s take a look at the code and how it functions. The first part of the code should be greyed out. That’s because it is a **comment**, or a note telling you about the program. This isn’t read by the computer at all. Comments start with the characters /* and they continue until they reach the characters */. Shorter comments are sometimes made with the characters //. Those comments only continue until the end of the line.

After the comments, there are two **functions** defined—**setup()** and **loop()**. A function is simply a piece of code that is named. In the Arduino environment, the **setup** and **loop** functions are special. The **setup** function runs once when the chip first turns on. It is used for things such as telling the chip which pins will be used for input and which ones will be used for output and doing other setup-related tasks. After the **setup** function completes, the **loop** function runs over and over again for as long as the chip is on.

If you look at the code, the **setup** function contains one command:

```
pinMode(13, OUTPUT);
```

This tells the microcontroller that digital output 13 (D13) will be used for output. Note that this refers to the D13 pin in Figure 15.1 (usually just labelled 13 on the Arduino Uno), not to pin 13 of the chip itself (which would be D7). With the Arduino Uno, we don’t actually need to worry about the pinout of the ATmega328/P, we just need to read the names of the pins next to the pin headers.

The **loop** function is the main part of the code. It looks like this:

```
digitalWrite(13, HIGH);
delay(1000);
digitalWrite(13, LOW);
delay(1000);
```

The first line (`digitalWrite(13, HIGH);`) says to turn D13 to HIGH, which is about 5 V. This provides the power for the LED attached to D13. This pin will remain high until we tell it to do something else.

The next line (`delay(1000);`) tells the chip to wait for 1,000 milliseconds (which is one second). During this time, nothing happens—the chip just waits. Changing this number changes the amount of time that the chip will wait for. Changing it to 500 will cause it to wait for half a second, and increasing it to 2000 (note that there are no commas in the number!) will cause it to wait for two seconds.

The next line turns D13 to LOW/false/off/0 V. This turns off the LED, because there is no longer any voltage supplied to it. D13 will stay in this state until told otherwise. The next line then waits for one second.

Once this function finishes, the chip will simply run the `loop` function again from the start.

Review

In this chapter, we learned:

1. A microcontroller is a small computer in a single microchip that provides customizable logic for handling digital signals.
2. A development board is a circuit board that simplifies the process of building circuits with a microchip by providing most of the standard connections for you, allowing you to focus your efforts on the things that make your project distinctive.
3. In order to use a microcontroller it has to be programmed from a computer.
4. The Arduino environment is a combination of software and hardware meant to make building microcontroller projects easier.
5. The Arduino Uno is a development board for the Arduino environment that includes a microcontroller, USB connection, power regulation, and headers for connecting the microcontroller's input/output pins to other circuits.
6. The ATmega328/P is the microcontroller used in the Arduino Uno.
7. An Arduino program (called a sketch) has two standard functions—`setup` (which is run once when the chip powers on) and `loop` (which runs over and over again as long as the chip is on).
8. Once a program is uploaded to the Arduino Uno, it will be saved on the device until another program is loaded.

Apply What You Have Learned

1. Practice modifying and uploading the Blink program to the Arduino Uno. Change the numbers given to `delay` to different values, and see how that affects the operation of the program.
2. The ATmega328/P is only one of many different microcontrollers available in the AVR family. Research online to find one or two other AVR chips and what different features they have.
3. The AVR family is only one of many microcontroller families. Research one or two other microcontroller families and look at what features are claimed for each. Examples of other microcontroller families include: PIC, STM32, MSP432, and the Intel Quark.
4. Go to the arduino.cc website and look at the different types of Arduinos that are available. What makes them different? Why might you choose one for a project over another?

Chapter 16

Building Projects with Arduino

Chapter 15 covered the basics of what microcontrollers are, what the Arduino environment is, and how to load a program onto an Arduino board. In this chapter, we will go into more depth on how to include an Arduino Uno into a project.

16.1 Powering Your Breadboard from an Arduino Uno

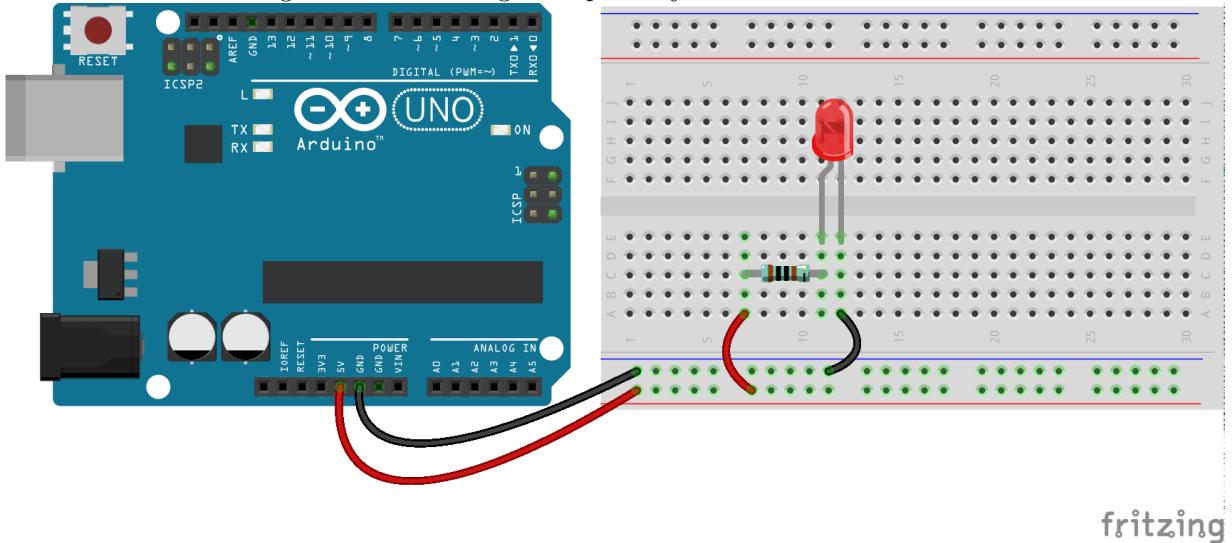
The first thing to understand about the Arduino Uno is that one of its main jobs is power regulation. As we saw in Chapter 15, the Arduino can use a variety of power sources—USB, battery, or a wall plug. Additionally, there is a connection on the Uno’s headers that allow for you to supply power from some other source.

If you have a power source that just has wires coming out of it—like a 9 V battery with a simple wire connector—the Uno has a place that you can plug it in. The pin labelled V_{IN} is used for supplying an unregulated voltage supply (7–12 volts) to the Uno (do not use the one labelled 5V). Therefore, if you plug the positive wire into V_{IN} and the negative wire into any of the GND pins (it doesn’t matter which one), then the Uno will spring to life.

On the flip side, you can actually power the rest of your project from the Uno, and take advantage of its voltage regulation, as well as its numerous methods for getting power. To do this, simply take a wire from the 5V connection on the Uno and connect it to the positive rail on your breadboard. Then, take another wire from one of the GND connections on the Uno and connect it to the ground rail on the breadboard. Viola! A very flexible 5 V power supply for your breadboard. Figure 16.1 shows how to use this to light a simple LED circuit.

Also note that there is also a 3.3 V connection if you need it, as many small devices are powered at that level.

Figure 16.1: Powering a Simple Project from an Arduino Uno



16.2 Wiring Inputs and Outputs to an Arduino Uno

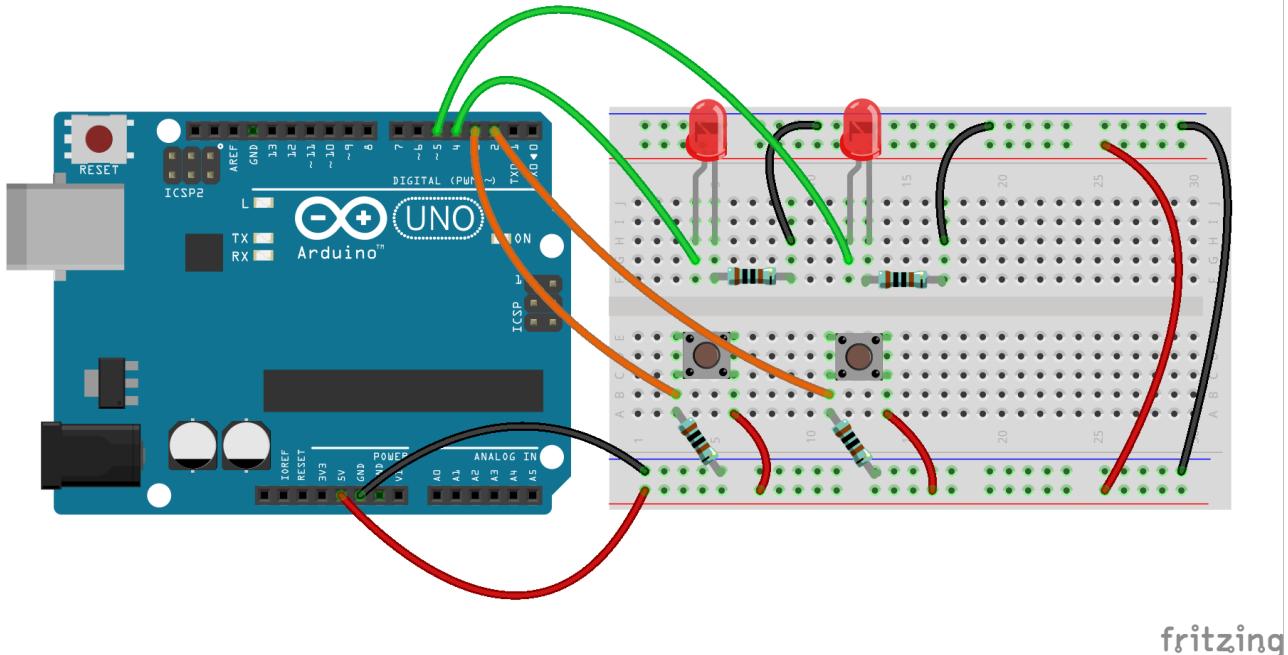
Now that we know how to power a breadboard from an Arduino Uno, we can now see how to connect inputs and outputs to the Uno.

Wiring inputs and outputs to an Uno is actually very easy. Outputs of the Uno can be viewed as simple voltage sources, like a battery, which operate at either 5 V (if set to HIGH) or 0 V (if set to LOW). Remember that any of the digital I/O pins can be set to be input or output pins in your Arduino program with the `pinMode` command.

However, even though an output pin can act as a voltage source, the current needs to be limited to prevent damage to the Arduino. Each output pin should only be sourcing up to 20 mA of current, and the total amount of output of all pins combined should never exceed 100 mA. So, for instance, if you have an LED output, be sure to add a resistor to limit the amount of current. Microcontrollers generally cannot drive high-power devices such as motors directly, and must use some sort of a power booster to do so. We will learn more about power later in the book.

Inputs to an Arduino are essentially voltage sensors. They will detect a HIGH (around 5 V) or LOW (near 0 V) signal on the pin. You can think of them as having a very large resistor attached to the front (about $100\text{ M}\Omega$ —one hundred million ohms), so they don't actually use up any serious amount of current. However, because they use so little current, that means that, just like our inputs in Chapter 12, they cannot be left disconnected, or the results may be randomized from static electricity in the air. Thus, for inputs, you should always attach a pull-up or a pull-down resistor (usually a pull-down) to the input to make sure that the input is *always* wired into the circuit in a known-valid state.

Figure 16.2: Wiring a Simple Button-based Arduino Project



16.3 A Simple Arduino Project with LEDs

In this section, we are going to look at making a simple Arduino project with two buttons, each controlling one of two LEDs. This would actually be simpler to wire without the Arduino, but the goal is to make a baby step to understanding how Arduino projects work.

This project is going to have buttons wired into Digital Pin 2 and Digital Pin 3 of the Arduino, and LEDs wired into Digital Pin 4 and Digital Pin 5. Let's think about what these need to look like. The LEDs will each need a current limiting resistor, and the buttons will each need a pull-down resistor.

Figure 16.2 shows how this should be wired up. The breadboard is being powered from the 5 V and GND terminals on the ARduino. The wires on the right side make sure power is connected to both sides of the breadboard. On the bottom, buttons are wired up with pull-down resistors and connected to Digital Pins 2 and 3 on the Arduino. On the top, the LEDs are connected to Digital Pins 4 and 5, with current limiting resistors making sure they don't draw too much current.

Now, of course, for an Arduino, this is not enough. The Arduino also needs a program to control it! Figure 16.3 shows the program you will need to type in to control the LEDs.

Note that, as usual, the project is divided into two pieces—`setup()`, which only occurs once when the chip starts up, and `loop()`, which continuously runs over and over again until the chip is turned off or reset. `setup()` simply tells which pins should be in which mode. Note that, unless it includes the calls to the

Figure 16.3: An Arduino Program to Control Two Buttons and Two LEDs

```
void setup() {
    pinMode(2, INPUT);
    pinMode(3, INPUT);
    pinMode(4, OUTPUT);
    pinMode(5, OUTPUT);
}

void loop() {
    // Turn pin 4 on/off based on
    // the input from pin 2
    if(digitalRead(2) == HIGH) {
        digitalWrite(4, HIGH);
    } else {
        digitalWrite(4, LOW);
    }

    // Turn pin 5 on/off based on
    // the input from pin 3
    if(digitalRead(3) == HIGH) {
        digitalWrite(5, HIGH);
    } else {
        digitalWrite(5, LOW);
    }
}
```

`delay()` function, the `loop()` function will literally run thousands of times per second (or more). The Arduino Uno can execute approximately 16 million instructions per second. Each line of code translates to many instructions, but nonetheless, it goes *really fast*. Just keep this in mind when you are writing programs.

Inside the `loop()` function we have a new Arduino function—`digitalRead()`. The `digitalRead` function takes a pin number and returns whether that pin is HIGH or LOW. We have put this into a conditional—if the read from the button pin is HIGH, then the corresponding LED pin is turned HIGH. Alternatively (i.e., `else`), if the read from the button pin is not HIGH (i.e., it is LOW), then the corresponding LED pin is turned LOW. Note that there are *two* equal signs used in the comparison. In many programming languages, you use two equal signs to tell the computer to compare values. A single equal sign often means that you are setting a value.

This book is not a book on computer programming, so we are not going to cover all of the details. Because of this, most of the programs will be given to you, and you will only need to make minor modifications. However, if you are interested in learning more, the programming language being used in the Arduino environment is C++, and the Arduino focuses on the easier-to-understand portions of it. **FIXME—Need a link to a good Arduino programming book**

16.4 Changing Functionality without Rewiring

Now, you might reasonably be thinking, “wouldn’t this be a lot easier if we just directly attached the buttons to the LEDs to turn them off and on?” Indeed, it would. However, by having the inputs and outputs all wired to the Arduino, we can actually *change* the functionality of the project *without* having to do a single bit of rewiring! For instance, if we wanted to have the left button control the right LED and the right button control the left LED, then all we would have to do is swap all of the 2s for 3s in the program, and vice-versa.

Now imagine if we had spent time developing such a device, and even had it sent off to manufacturing, but later decided that we wanted to change the functionality. If all of the parts are connected together by hardware, then that means that you have to throw away all of your old inventory to modify your functionality. If, instead, you use software to connect your components, then oftentimes you can update your device merely by updating your software.

Other modifications we can think of to this simple device might include:

1. making the LEDs turn off rather than on when the buttons are pressed
2. making the LEDs blink when the buttons are pressed
3. changing the buttons to be simple toggles, so that you don’t have to keep on holding the buttons down to keep the LED on
4. requiring that the buttons be pushed in a particular order in order to turn on the LED
5. requiring that both buttons be pushed to turn on the LEDs.

This list could go on and on. By routing all control processing through your microcontroller, you make your devices much more flexible. Additionally, at some point, they also become cheaper. When mass-producing, microcontroller chips like the ATmega328/P can be had for just over a dollar. Some chips, when purchased in bulk, cost less than fifty cents! So, if a microcontroller is replacing a complex sequence of logic gates and other control functionality, moving all of your control logic to a microcontroller can actually be much less expensive than hardwiring it, and you get added flexibility as a side bonus.

Chapter 17

Analog Input and Output on an Arduino

In Chapter 16, we learned how to do basic digital input and output with an Arduino using its I/O pins. In this chapter, we will cover how to do analog input and output as well.

17.1 Reading Analog Inputs

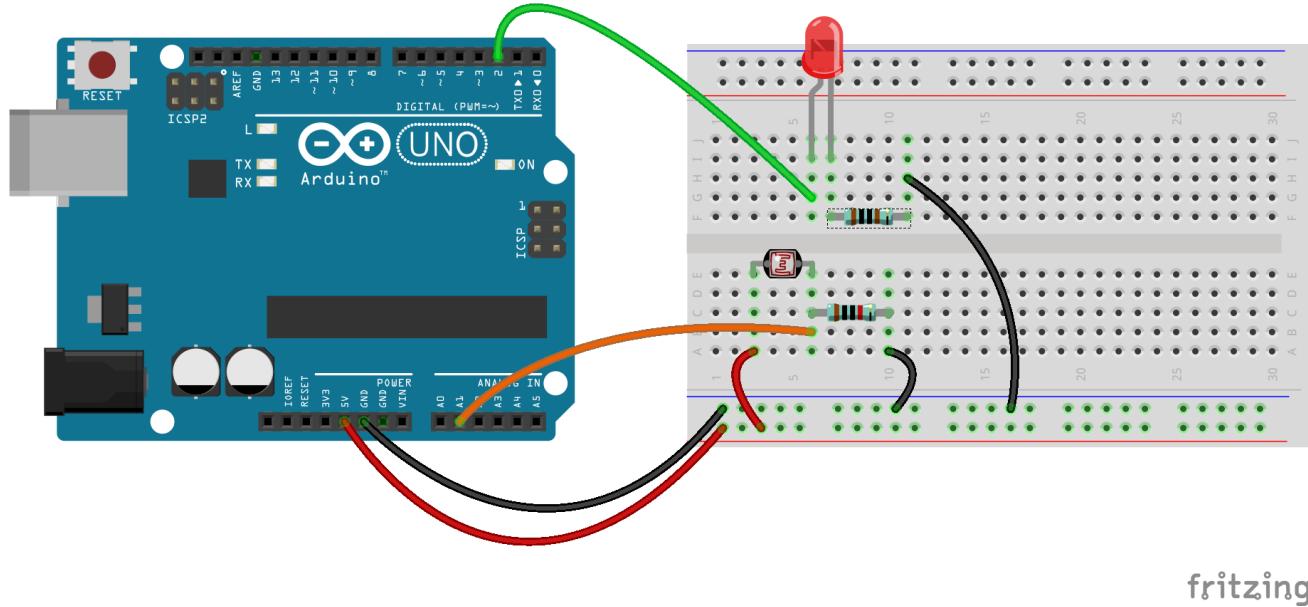
So far we have been focusing on digital input and output—HIGH and LOW states. The Arduino Uno also supports some amount of analog input (through its analog pins) and a sort of “faked” analog output (through its PWM pins, which will be covered in the next section).

On the Arduino Uno, the analog input pins are grouped together in a section labelled “Analog In.” These pins are voltage sensors similar to the digital I/O pins, but they can detect a range of values between 0 V and 5 V (you should never exceed 5 V on any Arduino pin). The `analogRead()` function is similar to the `digitalRead()` function in that it takes a pin number and returns an output value. The difference is that the pin number given to `analogRead()` corresponds to an analog input pin number, not a digital pin number, and the output, rather than being LOW or HIGH, is a number from 0 to 1023 (10 bits of resolution). 0 V will give you a 0, and 5 V will give you 1023.

Because of this, we can rework the darkness sensor we developed in Chapter 11 to use the Arduino. Since the photoresistor is just a resistor, we still need to use a voltage divider to convert the resistance value to a voltage. However, we no longer need the voltage comparator to get it to work—we can just directly connect it to an analog port on the Arduino!

Figure 17.1 shows the darkness sensor rebuilt for the Arduino. Notice that we have a lot fewer custom components, because the control has been moved from hardware to the Arduino’s software. We don’t need a reference voltage and we don’t need a voltage comparator. We just have one voltage divider to convert the photoresistor’s resistance to a voltage (with a wire going to the Arduino’s analog input pin 1), and an LED with a current limiting resistor for the output (fed from digital pin 2). Everything else comes from software.

Figure 17.1: The Darkness Sensor Rebuilt for Arduino



fritzing

Figure 17.2: Code for the Arduino Darkness Sensor

```
void setup() {  
    pinMode(2, OUTPUT);  
}  
  
void loop() {  
    if(analogRead(1) < 450) {  
        digitalWrite(2, HIGH);  
    } else {  
        digitalWrite(2, LOW);  
    }  
}
```

Figure 17.2 shows the code that will run the sensor. Note that in the `loop()` function, we are now using `analogRead()` rather than `digitalRead()`. Now, instead of it returning HIGH or LOW, it is returning a number. We can then compare that number to a baseline number to tell us whether we should turn the LED on or off.

Now, you may wonder where I got the value to compare against (i.e., 450). What I did was to test the sensor in a variety of conditions, and see which value turned off the light when I wanted it to!

However, you may be wondering what exactly are the values that it is reading. Thankfully, the Arduino environment allows a way for us to get feedback from the device while it is running, if it is connected to the computer. To do this, we use the what is known as the **serial** interface to the Arduino. This interface communicates over USB so that we can let our computer know how things are going in the program.

To use the USB serial interface, in your setup function you add the following line:

```
Serial.begin(9600);
```

This tells the chip to initialize its serial interface at 9600 baud (**baud** is an old term meaning “bits per second”), which allows us to talk back to the computer. However, it is important to note that if you use the `Serial` functions, you should not have anything connected to Digital Pin 0 or Pin 1 of the Arduino.

Now, in your program, you can do `Serial.println()` to output any value you want. We will do

```
Serial.println(analogRead(1));
```

to let us know what the current value of the analog input is reading at. The new program, with the added feedback, is shown in Figure 17.3. After uploading this code to the Arduino, to see your output, click on the magnifying glass on the top right of the screen. You can also go to the “Tools” menu and select “Serial Monitor.” Either way gets you to the same screen. When the code is running, it should be spewing out pages and pages of numbers. Each of these numbers is the current value of `analogRead()` when it is encountered in the code, which happens hundreds or thousands of times each second (it is slowed down a bit by the USB communication).

17.2 Analog Output with PWM

So, we have discussed analog *input*, but what about analog *output*. Truthfully, the Arduino does not support analog output as such. However, analog output is *faked* on an Arduino using a technique known as **pulse-width modulation**, abbreviated as **PWM**. The Arduino only outputs 5 V on its output pins. But, let’s say we wanted to fake a 2.5 V signal. What might we do? Well, if we turned the pin on and off rapidly so that it was only on for half the time, that would give us about the same amount of electricity as 5 V. That’s what PWM does—it fakes lower voltages by just flipping the power to the pin on and off very rapidly so that it “looks” like a lower voltage.

Arduino programs use the function `analogWrite()` to use a pin for PWM. This function is a little confusing because, (a) it uses digital pins, not analog pins, and (b) the value is between 0 and 255, not 0 and 1023 like `analogWrite()`. Other than that, it basically does what you might expect. `analogWrite(3, 0);` will turn

Figure 17.3: Darkness Sensor with Serial Feedback

```

void setup() {
    pinMode(2, OUTPUT);
    Serial.begin(9600);
}

void loop() {
    Serial.println(analogRead(1));
    if(analogRead(1) < 450) {
        digitalWrite(2, HIGH);
    } else {
        digitalWrite(2, LOW);
    }
}

```

off Digital Pin 3, `analogWrite(3, 255);` will turn it all the way on, `analogWrite(3, 127);` will flick it on and off pretty evenly, and `analogWrite(3, 25);` will keep Pin 3 on only a short time relative to how long the pin stays off.

To get a flavor for PWM, we will do a very simple PWM project—a dimmed LED. Figure 17.4 shows what the connection will look like. Just an LED with a current limiting resistor attached to Digital Pin 3 (which is marked with an `<` to indicate that it is capable of PWM). Figure 17.5 shows the code to dim the output.

This code is a little more complicated. It's alright if you don't understand it fully. In short, it creates a **variable**, which is a named temporary storage location for a value (we are calling it `i` for a short name). It is declared an **int**, which means it will hold an integer, and we set it with a starting value of zero.

The **while** loop executes everything within the block of code between `{` and `}` over and over again, as long as `i` is less than 255. Within this block, we write the value of `i` to pin 3 using `analogWrite()`. Then, we delay for 10 milliseconds to make sure it is visible. Then, we increase `i` by one to go to the next value.

The next **while** loop does the same thing but goes the other way. It starts at 255 and progresses down to 0. Then, when it is all the way to zero, it runs the `loop` function over again.

Even though this code is running by switching the pin on and off at different rates, it *looks like* the LED is dimming on and off. It is flickering so fast that we merely perceive it as a lower-energy light than as a pulsing light. In fact, when it gets to about 180 (about 70% on and 30% off), there is not a lot of difference between that and full brightness.

Figure 17.4: A Simple Analog Dimmer

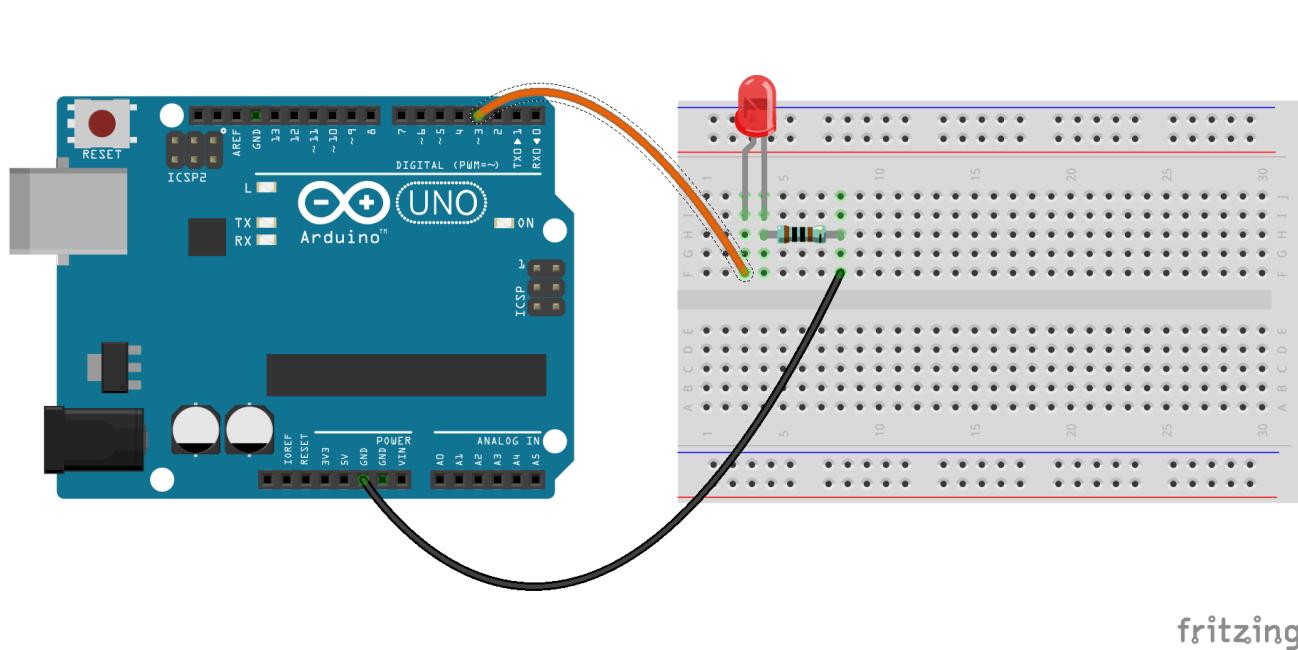


Figure 17.5: Code for the Analog Dimmer

```
void setup() {
    pinMode(3, OUTPUT);
}

void loop() {
    // Slowly turn the LED all the way up
    int i = 0;
    while(i < 255) {
        analogWrite(3, i);
        delay(10);
        i = i + 1;
    }

    // Slowly turn the LED all the way back down
    while(i >= 0) {
        analogWrite(3, i);
        delay(10);
        i = i - 1;
    }
}
```

Part IV

Capacitors and Inductors

Chapter 18

Capacitors

In this chapter we will start looking at the **capacitor**.

18.1 What is a Capacitor?

Before we begin discussing the capacitor, we need to quickly review the concepts from Chapter 3 on the relationship between charge, current, and voltage. In fact, it might be helpful to re-read that chapter if you find that you have forgotten how those terms related to each other.

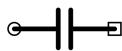
To review:

- Charge is essentially the amount of electrical “stuff” that something contains, measured in coulombs.
- Current is the *movement* of charge, measured in coulombs per second, also known as amperes.
- Voltage is the amount of force that each column will produce. You can think of it as the amount of electric energy that each coulomb is capable of producing, or the amount of power that each ampere of current yields.

A capacitor is a storage device which stores electric energy by holding two opposing charges (i.e., positive and negative). The amount of charge that the capacitors we will work with hold are very small, but some capacitors can store very large amounts of charge. One way to think of a capacitor is as a very, very, very tiny rechargeable battery. However, unlike batteries, instead of storing a fixed voltage, a capacitor stores opposing charges. The actual voltage a capacitor yields when it discharges will depend on both the size of the capacitor and the amount of charge it is holding.

The size of a capacitor is known as its **capacitance** and it is measured in **farads** (abbreviated with the letter F), named after the influential scientist Michael Faraday. A capacitance of one farad means that if

Figure 18.1: The Symbol for a Capacitor



a capacitor stores one coulomb of charge it will discharge with a force of 1 V. Most capacitors, however, have a capacitance much lower than a farad. Capacitors are usually measured in microfarads (1 millionth of a farad, abbreviated as μF or uF), nanofarads (1 billionth of a farad, abbreviated as nF), or picofarads (1 trillionth of a farad, abbreviated as pF). Capacitors are rarely rated in millifarads (1 thousandth of a farad).

So, to convert from microfarads to farads, multiply the capacitance by 0.000001. To go back from farads to microfarads, multiply the capacitance by 1000000. To convert from picofarads to farads, multiply the capacitance by 0.000000000001. To go back from farads to picofarads, multiply the capacitance by 1000000000000.

18.2 How Capacitors Work

The symbol for a capacitor in a circuit is shown in Figure 18.1. This symbol provides a visual reference for how a capacitor works. Capacitors usually work by having two conductors that are separated by some sort of non-conductive material. Since the two materials are near each other, the voltage difference between the two conductors will pull charge into the conductors. However, since they are not actually touching, the electrons cannot actually jump the gap. Therefore, the capacitor will accumulate a certain amount of charge and hold it in its conductors.

To understand this better, imagine that you are a positive charge. You are moving through the circuit, but why? What are you moving towards? As a positive charge, you are trying to move to the negative charge. So then, moving along, you see this big swimming pool (i.e., a capacitor). At the bottom of the swimming pool, the barrier is so thin that you can see to the other side. And what do you see there? It's the negative charges—right there at the bottom of the swimming pool! The negative charge has their own swimming pool the size of your own, separated by a barrier so thin that you can see each other.

Because you can see them, you go down into the swimming pool to see if you can interact. A lot of other bits of charge sees this, too, and they go down to see what is going on. However, when you get there, you realize that no matter how hard you try, you can't get to the negative charge that you can see. As more and more charge fills up the swimming pool, it starts to get crowded in the swimming pool. This creates *pressure* in the swimming pool—also known as *voltage*. As the swimming pool gets more and more crowded, it is harder and harder to fit new charge into it, and so the rate that it gets filled goes down, and the voltage goes up. The same thing is happening to the negatively-charged swimming pool on the other side.

When the pressure (voltage) to push charge out of the swimming pool equals the pressure (voltage) of the pipe (wire) leading to the swimming pool (capacitor), then the capacitor is full. When the voltage on the

wire goes down (i.e., the battery disconnects), then the pressure of the charges in the capacitor pushes them back out into the wire, discharging the capacitor.

FIXME—need graphic for this

So, if one terminal of the capacitor is connected to the positive side of a battery, and the other terminal is connected to the negative side of a battery, charge will quickly flow into the capacitor, as happened in our example with the swimming pool. The exact amount of charge that flows in depends on the voltage of the battery and the capacitance of the capacitor (i.e., the size of the swimming pool) .

There is an equation that tells you the amount of charge that can be stored in a capacitor for a given voltage:

$$Q = C \cdot V \quad (18.1)$$

In this equation, V is the voltage applied, C is the capacitance (in farads), and Q is the resulting charge (in coulombs).

Example 18.7 If I attached a $66\text{ }\mu\text{F}$ capacitor to a 9 V source, how much charge gets stored on the capacitor?

Well, first we need to convert the capacitance from microfarads to farads. $66\text{ }\mu\text{F}$ is 66 millionths of a farad, so it would be 0.000066 F . Now, we just need to plug the numbers into the equation:

$$\begin{aligned} Q &= C \cdot V \\ &= 0.000066 \cdot 9 \\ &= 0.000594 \text{ coulombs} \end{aligned}$$

Therefore, if I attached a $66\text{ }\mu\text{F}$ capacitor to a 9 V source, the capacitor would store 0.000594 coulombs of charge.

Likewise, if we know how much charge is stored in the capacitor, we can rearrange the equation slightly to figure out how much voltage it will deliver when it begins to discharge:

$$V = \frac{Q}{C} \quad (18.2)$$

Now, as the capacitor discharges, since the charge it is holding will decrease, so will the voltage it delivers.

Example 18.8 If I have a charge of 0.0023 coulombs stored in a $33\text{ }\mu\text{F}$ capacitor, if I discharge the capacitor, what voltage will it discharge at?

The first thing to do here is to convert the capacitance to farads. A microfarad is 1 millionth of a farad, so $33\text{ }\mu\text{F} = 0.000033\text{ F}$. Now we can just plug numbers into the equation:

$$\begin{aligned} V &= \frac{Q}{C} \\ &= \frac{0.0023}{0.000033} \\ &\approx 69.7 \text{ V} \end{aligned}$$

Therefore, when the capacitor discharges, it will discharge at 69.7 V.

18.3 Types of Capacitors

There are numerous types of capacitors available, each varying in the types of materials they are made of, the internal geometry of the capacitor, and the packaging.

FIXME—graphic of different types of capacitors

However, the most important feature of capacitors besides their capacitance is whether they are **polarized** or **non-polarized**. In a *non-polarized capacitor*, it doesn't matter which way you attach the leads. Either side can be the positive or negative. The most common type of non-polarized capacitor is the circle-shaped ceramic disk capacitor. While ceramic disk capacitors are easy to use, they suffer from having limited capacitance.

In a *polarized capacitor*, however, one lead *must* stay more positive than the other lead, or you risk damaging the capacitor. The most common type of polarized capacitor is the electrolytic capacitor. Electrolytic capacitors look like little barrels with leads coming out of them. They usually have much higher capacitances than ceramic disk capacitors, but you have to be sure that the polarity is correct and never switches direction.

On polarized capacitors, it is important to know which lead is positive and which is negative. There are several different ways that a manufacturer might indicate this:

1. One or both of the leads can be marked with their respective polarities (+ or -).
2. The negative lead can be marked with a large stripe.
3. The positive lead can be longer than the negative.

Many manufacturers do all three.

In a circuit schematic, if a polarized capacitor is called for, it will use a special capacitor symbol as shown in Figure 18.2. The only difference is that one side is curved. In a polarized capacitor, the straight side is the positive side and the curved side is the negative side. Sometimes polarized capacitors are marked with plus (+) and minus symbols (-) instead (or in addition).

On any capacitor, it is important to know the capacitance of the capacitor you are looking at. On larger capacitors (especially on electrolytics), manufacturers can print the full capacitance including the units

Figure 18.2: A Polarized Capacitor Symbol

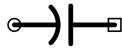
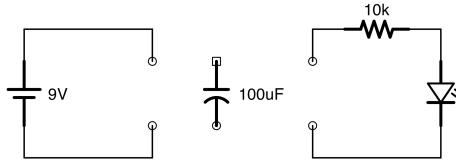


Figure 18.3: Using a Capacitor as a Battery



directly on the capacitor. However, many capacitors are extremely small, and can't fit that much information on them.

For smaller-sized capacitors, the capacitance is described by three digits and an optional letter. The third digit is how many zeroes to add to the end of the other two digits, and then the whole number is the capacitance in picofarads. So, if the number was 234, then the capacitance is 230,000 pF (23 followed by 4 zeroes). If the number was 230, then the capacitance is 23 pF.

The letter at the end tells the *tolerance* of the capacitor—how much the capacitance is likely to vary from its markings. Common letters are J ($\pm 5\%$), K ($\pm 10\%$), and M ($\pm 20\%$).

18.4 Charging and Discharging a Capacitor

To charge up a capacitor almost instantly you can connect the positive and negative leads of the battery to the leads of the capacitor. Once it is charged, you can use the capacitor as a very tiny battery for a project.

In Figure 18.3, we see two simple circuits and an electrolytic capacitor. For this circuit to really work, it helps to have an electrolytic capacitor at least $100\ \mu\text{F}$ and a resistor at least $10\text{k}\Omega$. So, first, build the LED circuit on the right side of Figure 18.3 on a breadboard. However, don't connect any power to the power rails. Next, take the capacitor, and touch the positive side to the positive terminal of the 9 V battery, and the negative side to the negative terminal. *Do not let the leads of the capacitor touch each other.* Hold it there for a second or two to allow the capacitor to fully charge. Now, *without touching the leads of the capacitor*, place the capacitor so that the positive lead goes into the positive rail of your breadboard and the negative lead goes into the negative rail of your breadboard. When you do this, the capacitor will power your LED project for a few seconds.

Now, you will notice that the LED gets dimmer before it goes out. Why does this happen?

Remember that the voltage that the capacitor yields is based on the charge that is present in the capacitor. So, going back to Equation 18.2, we can see that the voltage is based on the charge that is in the capacitor. When the capacitor is connected, it will start with a 9 V discharge, since that is what the battery was able to put into the capacitor. However, the capacitor is using up its charge to power the project. This means that as soon as its charge starts leaving, the voltage starts going down, since the voltage is related to how much charge is inside the capacitor.

Example 18.9 If we used the components listed in Figure 18.3, how much charge does the battery initially store in the capacitor?

We can use Equation 18.1 to determine this:

$$\begin{aligned} Q &= C \cdot V \\ &= 100 \mu\text{F} \cdot 9 \text{ V} \\ &= 0.000100 \text{ F} \cdot 9 \text{ V} \\ &= 0.0009 \text{ coulombs} \end{aligned}$$

Example 18.10 After 0.0003coulombs of charge have been discharged, what voltage is the capacitor discharging at?

To find this out, we first have to find out how much charge is *remaining* in the capacitor. So, to find this out, we just subtract the amount of charge that has been discharged from our starting charge. This gives $0.0009 - 0.0003 = 0.0006$ coulombs.

Now, we can use Equation 18.2 to find out what the voltage is that the capacitor is discharging at.

$$\begin{aligned} V &= \frac{Q}{C} \\ &= \frac{0.0006}{0.000100} \\ &= 6 \text{ V} \end{aligned}$$

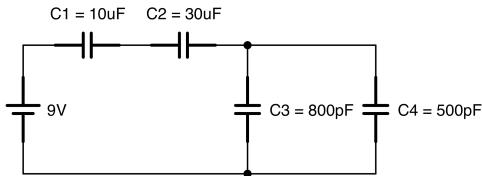
Therefore, the capacitor is discharging at 6 V

18.5 Series and Parallel Capacitances

Just like resistors, capacitors can be used either in series or in parallel. In fact, they use the same equations for series and parallel capacitance as do resistors. However, there is *one big difference*. The parallel and series versions of the equations are *reversed* for capacitors.

If we wanted to double resistance in a circuit we simply add another resistor of the same size in series. If I wanted to double my capacitance, I can add in another capacitor of the same size. However, for the

Figure 18.4: Capacitors in Series and Parallel



capacitor, we would add the capacitor *in parallel*. The following is the formula for adding capacitance in parallel:

$$C_T = C_1 + C_2 + \dots \quad (18.3)$$

If we want to put capacitors in series, we would use a formula that exactly like the formula for resistors in parallel:

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots} \quad (18.4)$$

Example 18.11 If I have a 100 μF capacitor in series with a 200 μF capacitor, how much total capacitance do I have?

To do this, we use Equation 18.4. It is best to convert our capacitances to farads first. It does not matter as long as the units are the same, but it is good practice to convert to farads so you don't forget when you start doing capacitances in different units. 100 μF is the same as 0.0001 F and 200 μF is the same as 0.0002 F. Now, we will plug these values into the equation:

$$\begin{aligned} C_T &= \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \\ &= \frac{1}{\frac{1}{0.0001 \text{ F}} + \frac{1}{0.0002 \text{ F}}} \\ &= \frac{1}{10000 + 5000} \\ &= \frac{1}{15000} \\ &= 0.0000666 \text{ F} && = 66.6 \mu\text{F} \end{aligned}$$

Example 18.12 Just like we did for resistors, we can combine a variety of parallel and series capacitances for a single capacitance value. For instance, take the circuit in Figure 18.4. What is the total capacitance of this circuit?

First, we can start by converting all of the capacitances to farads. This will make combining everything easier down the road. In that case, $C_1 = 0.00001\text{ F}$, $C_2 = 0.00003\text{ F}$, $C_3 = 0.000000008\text{ F}$, and $C_4 = 0.000000005\text{ F}$. C_3 and C_4 are in parallel, so we can combine them using the parallel formula (Equation 18.3):

$$\begin{aligned} C_T &= C_3 + C_4 \\ &= 0.000000008\text{ F} + 0.000000005\text{ F} \\ &= 0.000000013\text{ F} \end{aligned}$$

Now, if we substitute that capacitance in for C_3 and C_4 , we can use the series formula (Equation 18.4) to find the total capacitance of the circuit:

$$\begin{aligned} C_T &= \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_{3\&4}}} \\ &= \frac{1}{\frac{1}{0.00001} + \frac{1}{0.00003} + \frac{1}{0.000000013}} \\ &= \frac{1}{100000 + 33333.33 + 769230769.23} \\ &= \frac{1}{769364102.56} \\ &= 0.000000013\text{ F} \\ &= 1.3\text{ nF} \end{aligned}$$

So the total capacitance of the circuit is 1.3 nF .

18.6 Capacitors, AC, and DC Currents

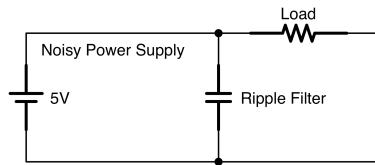
One important characteristic of a capacitor is that they *allow* the flow of AC (alternating current) but they *blocks* the flow of DC (direct current). To understand why this is, let's think about how capacitors operate.

Capacitors, when they are charging, essentially act as short circuits. As positive charge flows into the capacitor at one terminal, negative charge flows in to the other side. An *inflow* of negative charge to that side means that there is a net *outflow* of positive charge on that side. So, even though the physical electrons never cross the boundary between the plates, the total charge actually moves from one side to the other.

However, this situation is temporary because, as the capacitor gets more full of charge, new charge is less likely to enter. Once the capacitor is fully charged (based on the voltage), no new charge can flow in to one side to cause the charge to go out to the other.

Once the capacitor is charged, *current stops flowing through it*. If the voltage level on one of the leads *changes*, then charge will flow until the change is compensated for by the capacitor charging or discharging.

Figure 18.5: A Capacitor Filtering a Noisy Power Supply



Thus, it is only when the voltage *changes* that the current flows. If the voltage stays the same, then charge will stop flowing through the capacitor as soon as it reaches capacity for that voltage.

Because of this, we say that capacitors *allow AC* but *block DC*. This rule of thumb will help us use capacitors in a variety of circuits later on.

18.7 Using Capacitors in a Circuit

In this section we will discuss the uses of capacitors in a circuit. We haven't discussed enough to actually use capacitors in these ways, but I thought it would be helpful to see why capacitors are used so you can see why you should care about these things.

The first thing that capacitors are used for is for filtering noisy signals, especially in power sources. Imagine that you had a power source which, instead of delivering a constant voltage, the voltage would wobble a bit. If you placed a capacitor in parallel with this circuit, the power source would charge the capacitor up. Then, if the power source dropped a bit, the capacitor would start discharging to compensate. Likewise, if the power source increased, the capacitor would absorb some of that increase by storing the charge.

Thus, by acting as a temporary location to store extra charge, the capacitor can smooth out ripples in a signal, as seen in Figure 18.5. This sort of usage is known as a *filtering* capacitor because it filters out noise.

This can be seen as another implementation of our rule that capacitors allow AC current to flow but block DC. When the source voltage has a ripple, the *ripple itself* gets shunted to ground by the capacitor. However, under normal operation, the DC part of the current can't flow through the capacitor, and just continues on to the load.

On many ICs that have fluctuating power requirements, you will find many of their spec sheets recommending one or more capacitors on their power supply or other pins in order to filter out the noise.

Another way of using capacitors is as a **coupling capacitor**. A coupling capacitor is used when you have *both* an AC signal and a DC signal combined. This will happen a lot when we talk about amplification. What happens is that we will have an amplified signal, but we *only* want the AC portion of the signal. We can do that by adding in a capacitor to join the segment of the circuit that has both AC and DC components to the segment of the circuit that only wants the AC component.

Another way that capacitors are used is for filtering specific frequencies. Higher-frequency signals are easily transmitted, but low-frequency signals are essentially blocked as if it were DC current. The frequencies that are allowed are based on the capacitance. If you put a capacitor in series with the signal path, then it will only allow higher frequencies. If you put a capacitor in parallel with the signal path, then it will only allow lower frequencies (the higher frequencies will be shunted to ground).

Review

In this chapter, we learned:

1. A capacitor is a device that stores electric energy by holding two opposing charges.
2. Capacitors are sized by their capacitance which is measured in farads.
3. Because a farad is so large, capacitors are usually measured in microfarads, nanofarads, and picofarads.
4. Polarized capacitors (usually electrolytic capacitors) have distinct positive and negative terminals, while non-polarized capacitors (usually ceramic disk capacitors) can go either way.
5. When a battery is connected to a capacitor, it will store a charge on the capacitor.
6. The equation for the charge (Q) stored on the capacitor when a battery is connected is $Q = C \cdot V$ where C is the capacitance in farads, V is the voltage, and Q is the charge in coulombs.
7. By rearranging the equation, we can determine, for a given amount of charge, how much voltage a capacitor will discharge when it is allowed to: $V = \frac{Q}{C}$.
8. As the capacitor discharges its charge through the wire to create current, the amount of charge remaining will decrease, which will also lower the voltage it is putting out.
9. Capacitors with small packages are often marked with a three-digit code, where the third digit is the number of zeroes to add to the other two digits, and the final number is in picofarads.
10. When multiple capacitors are used together, their capacitances can be combined similar to resistors, but with the series and parallel equations switched.
11. Series capacitance equation: $C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots}$
12. Parallel capacitance equation: $C_T = C_1 + C_2 + \dots$
13. Capacitors allow the flow of AC current through them but block the flow of DC current.
14. Capacitors can be used to split AC (high-frequency) and DC (low-frequency) portions of a signal. The AC portion will travel through the capacitor while the DC portion will remain on one terminal side.
15. Capacitors can be used to filter audio frequencies, filter power supply ripples, operate as voltage boosters, and couple together a combined AC/DC circuit with an AC-only circuit.

Exercises

1. Convert 23 F to microfarads.
2. Convert $15\text{ }\mu\text{F}$ to farads.
3. Convert 0.0002 F to microfarads.
4. Convert $0.0030\text{ }\mu\text{F}$ to farads.
5. If a voltage of 6 V is applied to a $55\text{ }\mu\text{F}$ capacitor, how much charge would it store?
6. If a voltage of 2 V is applied to a 13 pF capacitor, how much charge would it store?
7. If a $132\text{ }\mu\text{F}$ capacitor is holding 0.02 coulombs of charge, how many volts will it produce when it discharges?
8. If a 600 pF capacitor is holding 0.03 coulombs of charge, how many volts will it produce when it discharges?
9. If a $121\text{ }\mu\text{F}$ capacitor is connected to a battery. After some fluctuation, the capacitor has 0.00089 coulombs of charge stored in it and the battery is reading 8.9 V . Is the capacitor going to be charging or discharging at this point?

Chapter 19

Capacitors as Timers

In this chapter, we are going to learn how to use measure the time it takes for a capacitor to charge. Once we learn this, we can use capacitors for timers—both for delaying signal as well as for creating an oscillating circuit.

19.1 Time Constants

As we learned in Chapter 18, when a voltage is applied to a capacitor it will store energy by storing a charge on its plates, the amount of charge being based on the voltage supplied (see Equation 18.1). However, if a capacitor charges through a resistor, then it takes much longer to fill the capacitor to capacity than if it were connected to the battery directly. In fact, it never *fully* reaches capacity, though it gets close enough that we say that it does.

Having a resistor in series with a capacitor is a configuration known as an **RC circuit**. The amount of time it takes a capacitor to charge is based on both the resistance of the resistor and the capacitance of the capacitor. The actual equation for this is kind of complicated but there is a simple trick that suffices for nearly every situation, known as the RC time constant.

The RC time constant is merely the product of the resistance (in ohms) multiplied by the capacitance (in farads) which will yield the RC time constant in seconds. The RC time constant can be used to determine how long it will take to charge a capacitor to a given level. So, for instance, if I have a $100\ \mu\text{F}$ capacitor and a $500\ \Omega$ resistor, the RC time constant is $0.0001 * 500 = 0.05$ seconds.

This constant can then be used with the table in Figure 19.1 to determine how long it will take to charge a capacitor to a given level.

For instance, if I wait for 2 time constants (in this case, $0.05 \cdot 2 = 0.1$ seconds), my capacitor will be charged to 86.5% of the supply voltage. The current flowing through it will be at 13.5% of what current would be flowing if there was just a straight wire instead of a capacitor.

Figure 19.1: RC Time Constants

# of Time Constants	% of Voltage	% of Current
0.5	39.3%	60.7%
0.7	50.3%	49.7%
1	63.2%	36.8%
2	86.5%	13.5%
3	95.0%	5.0%
4	98.2%	1.8%
5	99.3%	0.7%

While a capacitor is never really “fully charged” (because it never fully reaches 100%), in this book, we will use 5 time constants to consider a capacitor fully charged.

Example 19.13 I have a power supply that is 7 V and a capacitor that is a 100 μF capacitor. I want it to take 9 seconds to charge my capacitor. What size of resistor do I need to use to do this?

To solve this problem, we need to work backwards. Remember, we are considering 5 time constants to be fully charged. Therefore, the time constant we are hoping to achieve is $9/5 = 1.8$ seconds. The capacitance is 100 μF , which is 0.0001 F. Since the time constant is merely the product of the capacitance and resistance, we can solve for this as follows:

$$\text{RC Time Constant} = \text{capacitance} \cdot \text{resistance}$$

$$1.8 = 0.0001 \cdot R$$

$$0.0001 \cdot R = 1.8$$

$$R = \frac{1.8}{0.0001}$$

$$R = 18000$$

Therefore, to make it take 9 seconds to charge the capacitor, we need to use an 18 k Ω resistor.

In the same way, if we connect the capacitor to ground through the resistor instead of to the voltage supply, the capacitor will discharge in the same way that it charged. It will begin discharging a lot, but then, as it gets closer to zero, it will level off the amount that it is discharging. You would then read Figure 19.1 to be the percentage *discharged* that the capacitor was.

Example 19.14 Suppose a 100 μF capacitor has been charged up to 7 V and then is disconnected from the power supply, but the ground connection remains. We then connect

the positive terminal of the capacitor to a $5\text{ k}\Omega$ resistor that connects to ground. After 2 seconds, how much voltage is remaining in the capacitor?

To find this out, we first need to find the RC time constant of the circuit.

$$\begin{aligned} T &= 5\text{ k}\Omega \cdot 100\text{ }\mu\text{F} \\ &= 5,000\text{ }\Omega \cdot 0.0001\text{ F} \\ &= 0.5\text{ seconds} \end{aligned}$$

So the RC time constant is 0.5 seconds.

So, after 2 seconds, we have performed 4 RC time constants. Looking at Figure 19.1, we have discharged 98.2% of the capacitor's voltage. This means that the amount of voltage *lost* should be $0.982 \cdot 7\text{ V} = 6.874\text{ V}$. If we have lost that much voltage, that means we should subtract it, so the remaining voltage is $7\text{ V} - 6.874\text{ V} = 0.126\text{ V}$.

So the voltage after 2 seconds will be 0.125 V.

19.2 Constructing a Simple Timer Circuit

Let's say that we want a circuit that, when turned on, *waits* for a certain amount of time and then does something. How might we do it?

Think of it this way. We can use capacitor charging to give us a time delay. However, we need something that "notices" when the time delay is finished. In other words, we need a way to trigger something when a certain threshold is crossed.

What happens to the capacitor as it charges? The voltage across its terminals changes. When it is first connected to the circuit, there is zero voltage across its terminals. As it charges, the voltage across the capacitors terminals keeps going up until it matches the supply voltage. Therefore, we know when we have hit our target time based on when the voltage is at a certain level. But how will we know when we are at the right voltage? Have we done a circuit so far that detects voltages? What component did we use?

If you remember back to Chapter 11, we used the LM393 to compare voltages. We supplied the LM393 with a *reference* voltage, and then it triggered when our other voltage went above that voltage. We can do the same thing here.

What we will construct is a circuit that waits for 5 seconds and then turns on an LED. In order to do this, we will need to choose (a) a reference voltage to use, (b) a resistor/capacitor combination that will surpass the reference voltage after a certain amount of time, and (c) an output circuit that lights up the LED.

There are virtually infinite combinations we could choose from for our reference voltage, resistance, and capacitance. In fact, the supply voltage doesn't matter so much since what we are looking at is *percentages* of the supply voltage, which will be the same not matter what the actual voltage is.

For this example, we will use a basic 5 V supply, and make the reference voltage to be half of the supply voltage. This allows us to use any two equivalent resistors into a voltage divider to get our reference voltage.

Technically the voltage itself does not matter nearly as much as the fact that we are using half of the supply voltage as our reference voltage.

Now, since the reference voltage is half of our supply voltage, we will use the table in Figure 19.1 to determine how many time constants that needs to be. The table says that for 50% of voltage, it will take 0.7 time constants (it is actually 50.3%, but we are not being that exact).

Therefore, the equation for our resistor and capacitor is

$$\begin{aligned} T &= 5 \text{ seconds} \\ 5 \text{ seconds} &= 0.7 \cdot R \cdot C \\ \frac{5}{0.7} &= R \cdot C \\ 7.14 &= R \cdot C \end{aligned}$$

So, we can use any resistor and capacitor such that the ohms multiplied by the farads equals 7.14. I usually use 100 μF capacitors for larger time periods such as this because they are larger and because being exactly 0.0001 F it makes it easier to calculate with. Therefore, we can very simply calculate the needed resistor for this capacitor.

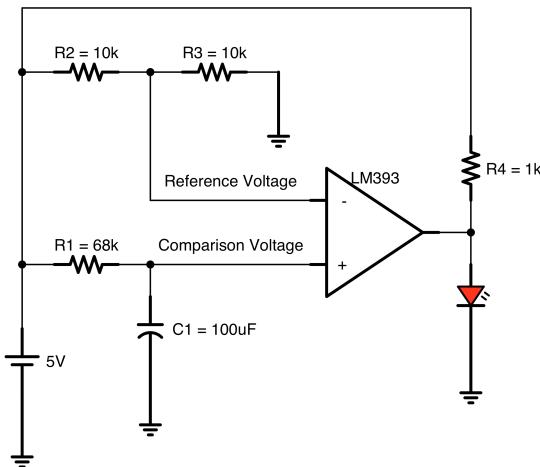
$$\begin{aligned} 7.14 &= R \cdot C \\ 7.14 &= R \cdot 0.0001 \\ \frac{7.14}{0.0001} &= R \\ 71400 &= R \end{aligned}$$

Therefore, we need a resistor that is about 71,400 Ω . We could choose a combination of resistors that hits this exactly, but for our purposes, we only need to get close. In my case, the closest resistor I have is 68,000 Ω (i.e., 68 k Ω). That is close enough (though I could get even closer by adding in a 3 k Ω resistor in series).

Figure 19.2 shows the full circuit. When building this circuit, don't forget that the comparator also has to be connected to the supply voltage and ground as well! As you can see, R2 and R3 form the voltage divider that provides the reference voltage for the comparator at half of the supply voltage. The values for R2 and R3 are arbitrarily chosen, but they must be equal to get the reference voltage. I chose medium-high values for these resistors so as to not waste current with the voltage divider. The circuit made by R1 and C1 is the timing circuit. When the circuit is first plugged in, C1 is at voltage level 0, essentially acting as a short circuit while it first begins to store charge. At zero volts, this is obviously less than our reference voltage. However, as the capacitor charges, less, and less current can flow into C1. Its voltage level increases under the rules of the RC time constant. After 0.7 time constants, the voltage will be above the voltage level set by the reference voltage, and our voltage comparator will switch on.

Remember, though, from Chapter 11, that the LM393 operates using a pull-up resistor. That is, the comparator doesn't ever source current. It will sink current (voltage level 0 when the + input is less than

Figure 19.2: A Simple Timer for an LED



the - input), or disconnect (when the + input is greater than the - input). Therefore, R4 is providing a pull-up resistor to supply power to the LED when the LM393 disconnects.

Figure 19.3 shows this circuit laid out on the breadboard. We are using the second voltage comparator of the LM393 just because it was a little easier to show the wiring for it. If you need to see the pinout for the LM393 again, it was back in Figure 11.4.

Notice the prominence of our basic circuits from Chapter 9. On the top, we have a combination pull-up resistor which is also acting as a current-limiting resistor (as they often do). On the bottom left, we have a voltage divider.

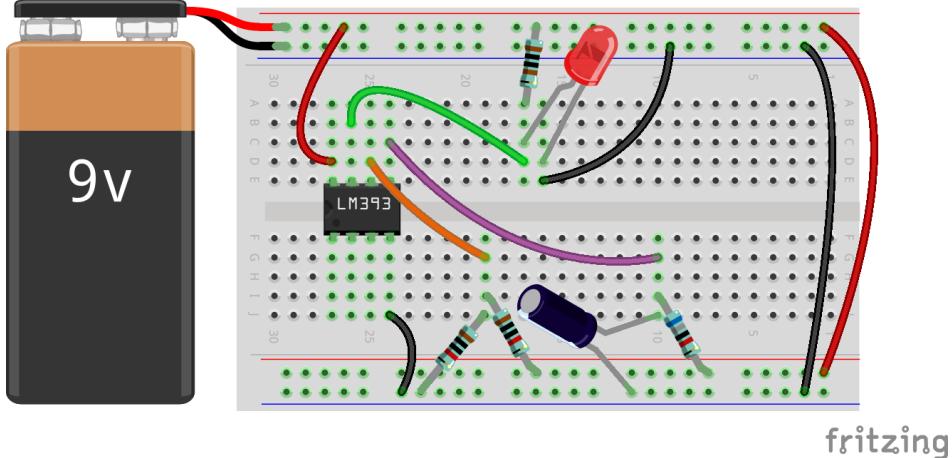
On the bottom right, we have our new timing circuit, which looks a lot like a voltage divider. In fact, it acts like one, too, where the voltage varies by time! If you think about what the capacitor is doing, when we first apply voltage it acts like a short circuit—in other words, no resistance. This means that there are zero volts across the capacitor, and the resistor is eating up all of the voltage. But, as the capacitor fills up, it increases voltage, which it is *dividing* with the resistor!

19.3 Resetting Our Timer

The timer is great, except for one thing—how do we turn it off? You might have noticed that, even if you disconnect power to the circuit, when you turn it back on, it doesn't do any timing anymore! Remember, the capacitor is *storing* charge. When you turn off the circuit, it is *still* storing the charge.

Now, you can very simply get rid of the charge by putting a wire between the legs of the capacitor. However, for larger capacitors, you would need to do this with a resistor instead of a wire in order to keep there from

Figure 19.3: The Capacitor Timer Circuit on a Breadboard



being a dangerous spark (the resistor limits the current, which makes the discharge slower). But how do we do this with a circuit?

What we can do is add a switch that will do the same thing as putting a wire or resistor across the legs of the capacitor. Figure 19.4 shows how to do this.

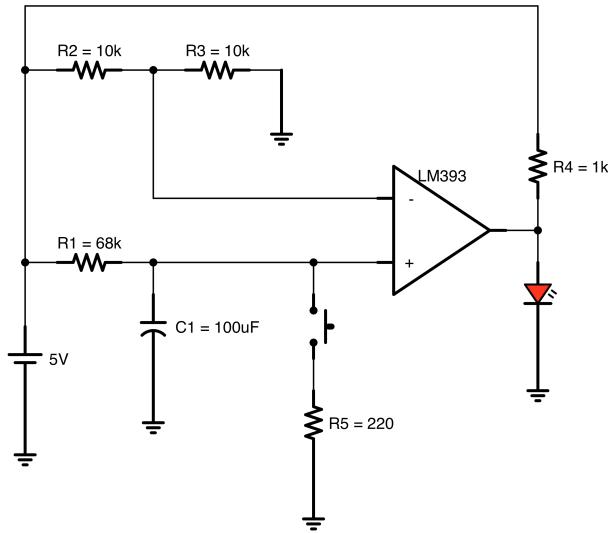
Now let's look at how this circuit works. First of all, we added two components, the switch and the R5 resistor connected to it. To understand what this does, pretend for a minute that the resistor isn't there. What happens when we push the button? That would create a direct link from the positive side of the capacitor to ground. Since the negative side of the capacitor is also connected to ground, that means that these two points would be directly connected. Thus, they would be at the *same* voltage. This would happen by the current suddenly rushing from one side to another.

If the capacitor were larger or the voltages greater, this might be somewhat dangerous. You would have a large current and a large voltage for a short period of time (which would yield a large wattage), which could blow something out. Therefore, it is good practice to use a small resistor between the button and ground. The resistor should be *much* smaller than the resistor used to charge the capacitor. The specific size doesn't matter too much—it needs to be small enough to discharge it quickly and large enough to prevent a spark when you push the button. You can use the same time constants for discharging the capacitor that you used for charging it. However, keep in mind that the charging circuit is still running! That's why the resistor has to be small—it has to discharge the capacitor *while* the other resistor is trying to charge it.

Also notice R1 and R5. When the button is being pushed, what is happening to them? Think back to our basic resistor circuits. If we have two resistors, with a wire coming out of the middle, what is that? It's a voltage divider! So, not only is R5 being a current-limiting resistor for the button, it is also acting as a voltage divider in concert with R1.

What this means is that the capacitor will only discharge down to the level of voltage division between these resistors. That's fine, as long as it is low enough. You will find that in electronics, "close enough" often

Figure 19.4: Adding a Reset to the Capacitor



counts. The trick is knowing how close is close enough and how close is still too far.

However, usually we can perform some basic calculations to figure this out. Since R_1 is $68\text{ k}\Omega$ and R_5 is 200Ω , what is the voltage at the point of division? If we use a 9 V supply, then using the formula from Equation 9.1 then we can see that:

$$\begin{aligned}
 V_{OUT} &= V_{IN} \cdot \frac{R_5}{R_1 + R_5} \\
 &= 9 \cdot \frac{220}{68000 + 220} \\
 &= 9 \cdot \frac{220}{68220} \\
 &\approx 9 \cdot 0.00322 \\
 &\approx 0.029\text{ V}
 \end{aligned}$$

So, as you can see, when the button is pushed, the final voltage of the capacitor, while not *absolutely* zero volts, is pretty darn close.

Also note that, if we wanted, we can reverse the action of this circuit. By swapping our two inputs to the voltage comparator, we can make the circuit be on for 5 seconds and then switch off.

Review

In this chapter, we learned:

1. A resistor and capacitor in series with each other is known as an RC circuit.
2. In an RC circuit, the amount of time it takes for a capacitor to charge to the supply voltage is based on the capacitance of the capacitor and the resistance of the resistor.
3. The RC *time constant* is a convenient way to think about how long it takes for a capacitor to charge in RC circuits.
4. The RC time constant is calculated by multiplying the resistance (in ohms) by the capacitance (in farads) with the result being the number of seconds in 1 RC time constant.
5. The table in Figure 19.1 shows how long it takes to charge a capacitor to different percentages of supply voltage as a multiple of RC time constants.
6. The RC time constant chart can also be used to calculate the amount of time it takes for a capacitor to discharge to ground if it is disconnected from its source and connected through a resistor to ground. In this case, Figure 19.1 is used to tell the percentage that the voltage has been *discharged*.
7. A timer can be constructed by using a comparator and an RC circuit along with a reference voltage provided by a voltage divider. By tweaking the RC circuit, the timing can be changed.
8. After charging a capacitor, a means needs to be provided to discharge it as well, such as a button leading to ground.
9. Such discharge methods need to have resistance to prevent sparks and other failures, but not too much resistance as they can accidentally form voltage dividers with other resistors.
10. Even as our circuits get more advanced, the basic circuits we found in Chapter 9 are still dominating our circuit designs.

Apply What You Have Learned

1. If I have an RC circuit with a resistor of $10\ \Omega$ and a capacitor of 2 F , what is the RC time constant of this circuit?
2. In the previous question, how many seconds does it take to charge my capacitor to approximately 50% of supply voltage?
3. If I have an RC circuit with a resistor of $30,000\ \Omega$ and a capacitor of 0.001 F , what is the RC time constant of this circuit?
4. In the previous question, what percentage of the way is the capacitor charged after 60 seconds?
5. If I have an RC circuit with a resistor of $25\text{ k}\Omega$ and a capacitor of $20\text{ }\mu\text{F}$, what is the RC time constant of this circuit?

6. Give a resistor and capacitor combination that will yield an RC time constant of 0.25 seconds.
7. Reconfigure the circuit in Figure 19.2 to wait for 3 seconds. Draw the whole circuit.
8. Redraw the previous circuit, and circle each basic circuit pattern and label it.

19.4 Oscillator Circuits

In Chapter 19, we learned how to use RC (resistor-capacitor) circuits to create timers. In this chapter, we are going to use our concept of timing circuits to move from one-time timer circuits to *oscillating* circuits.

19.5 Oscillation Basics

So far, most of the circuits we have made have been fairly directional. You do an action (i.e., press a button) and then something happens, but then the circuit just maintains a steady-state after that. In Chapter 19, we at least added a delay—allowing the circuit to do something *later*.

However, if you want actions to continue on into the future, you need to not only have delays, you need to have *oscillations*. **Oscillation** means to go back and forth. An oscillating circuit is one that goes back and forth continually between two states—usually zero voltage and some positive voltage. Imagine blinking lights at Christmas. These lights go from a state of zero voltage (off) to a state of positive voltage (on). And they go back and forth between these states over and over again as long as there is power in the circuit. These are oscillating circuits.

An oscillator is usually described by either its **wavelength** or its **frequency**. The wavelength of an oscillator is how many seconds it takes to go through one complete cycle. So, if I had lights that blinked on for one second and then off for two seconds (and continued repeating in that fashion), the wavelength would be three seconds.

The frequency of an oscillation is the number of times that the wave cycles every second, which is merely the reciprocal of the wavelength (i.e., one divided by the wavelength). So, in the example given, since the wavelength was 3 seconds, the frequency is $\frac{1}{3}$ cycles per second. The unit “cycles per second” also has a special name—**hertz** (often abbreviated as **hz**). Therefore, we would say that our blinking lights blinked at a frequency of 3 Hz.

Example 19.15 Let’s say that we have an oscillator that turns a light on for four seconds and then turns off for four seconds, and repeats this continually. What is the wavelength and frequency of this oscillator?

The wavelength is merely the total time it takes to go through one complete cycle. Therefore:

$$\begin{aligned}\text{wavelength} &= 4\text{seconds} + 4\text{seconds} \\ &= 8\text{seconds}\end{aligned}$$

So, what is the frequency of this oscillator? Simple, just take the reciprocal of the wavelength. That makes the frequency $\frac{1}{8}$ Hz.

Example 19.16 On a piano, the Middle-C key plays a sound with a frequency of 261.6 Hz. What is the wavelength of this sound?

Since the frequency is the reciprocal of the wavelength, it works the other way around as well—wavelength is the reciprocal of the frequency. Therefore, the wavelength is simply $\frac{1}{261.6}$ seconds. Or, as a decimal, this is 0.00382 seconds.

19.6 The Importance of Oscillating Circuits

Oscillating circuits are important in electronics for a number of reasons. First, obviously, is blinky lights. Who goes into electronics without being enamored by blinking lights? But, more importantly, the following are all applications of oscillators in circuits:

Sound production Sounds and tones are made by moving a speaker back-and-forth, which is moved back and forth by electricity oscillating between different voltages.

Time clocks Every clock on earth operates by an oscillator. The clock simply counts the number of oscillations that have occurred to know whether or not to advance another minute.

Hardware coordination clocks In computers and other advanced hardware, system events are coordinated based on signals from an oscillating circuit. When the clock changes state from off to on, then the circuit does the next step in the process. The clock keeps the different circuits from interfering with each other.

Radio transmissions Oscillators are used in radios in order to encode signals onto “carrier waves,” which are just oscillating signals run at a specific frequency.

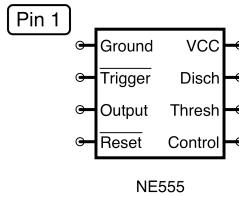
Servo Motors A servo is a motor which moves an arm to a specific angle (i.e., think of a car’s steering). Servos are usually operated by frequencies, where each frequency specifies a different angle to move.

Let’s look in more depth about sound is produced by oscillation. You hear sound through your eardrum, which communicates vibrations it detects to your brain which you interpret as sound. Therefore, any sound that you hear is merely the vibrations of your eardrum. In other words, your eardrum *oscillates* back and forth, which you interpret as sound.

What makes your eardrum move back and forth? The answer—oscillations in the air. What makes those oscillations happen? Oscillations in the sound speaker. When the speaker moves back and forth, it moves the air which produces sound that you hear.

But what moves the speaker back and forth? Oscillations in the voltage and current supplied to the speaker. The speaker has a magnet attached to it which responds to changes in voltage in the wire. As the voltage in the wire increases, it moves the speaker in one direction. As the voltage decreases, the speaker moves in the other direction. Thus, the oscillations in voltage eventually wind up as sound for your ears.

Figure 19.5: The 555 Pinout Diagram



19.7 Building an Oscillator

Let's think for a moment of what it would take to build an oscillator. You have at least two different states—on and off. You *can* build an oscillator with more than two states, but we won't be concerned with such things in this book. Then, you have a time period between the two states. What sort of circuit have we looked at that provides a time period?

As we saw in Chapter 19, RC (resistor-capacitor) circuits can provide us with time delays. We can then use these time delays as the time periods between the states of the oscillation. What we need is a circuit that will give out a state (we'll call it S1) for a time period (we'll call it T1) and then move to another state (we'll call it S2) and stay there for another time period (we'll call it T2).

Now, it is possible that we might be able to build such a circuit using multiple RC timers with multiple comparators. It is doable, but it is harder than it sounds. Thankfully, there is an integrated circuit that is built for making such timers—the NE555, often referred to as just a “555 timer” or just a “555.” The NE555 is a very flexible component, and engineers are constantly finding new ways to make use of it. However, we will just focus on using it as a basic oscillator.

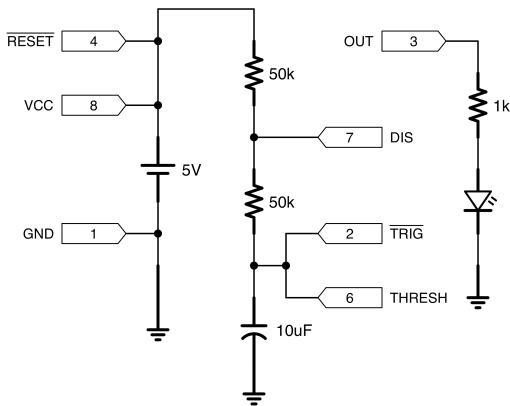
It is easiest to describe how a 555 works if we start out by showing a simple circuit with it. The circuit in Figure 19.6 blinks an LED on and off.

The order of the pins on the actual 555 chip is a little confusing. In order to make it easier, I have simply put tags for each pin, so you can see where they each belong *functionally*.

First, let's look at the pins on the left-hand side that are directly connected to the power rails. Pin 1 (*Ground*) and Pin 8 (*VCC*) are easy enough—they are connected to ground and positive voltage, respectively. Pin 4 (*Reset*) gets connected to the voltage source, too. That is a reset pin which is activated if the pin receives a *low* voltage signal. Pins that are activated by low-voltage signals are often shown with a line over them. In our case, we never want to reset the chip, so we just tie the reset pin to positive voltage, which will prevent any accidental resets from changes in voltages in the air.

Now, on the right-hand side at the top, you can see the LED connected to Pin 3 (*Output*). Pin 3 is simply the output pin. It is an active output, meaning that it will supply current to the output on its own. We don't need a pull-up resistor like we did for the LM393. Instead, we just need a current-limiting resistor for the LED. The regular NE555 output yields a voltage that is about 1.7 V less than the supply voltage, and sources up to 200 mA before it breaks.

Figure 19.6: A Schematic of a Simple 555 Oscillation Circuit



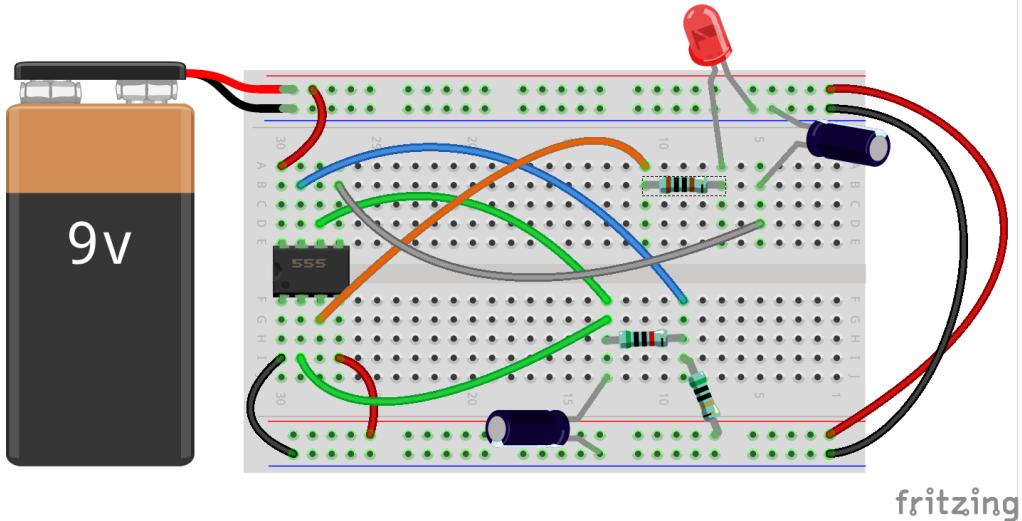
Note that there are other, low-power versions of the 555 timer that have other output characteristics. For instance, the LMC555 has an output voltage that is equal to the input voltage, but can only source about 100 mA. For our purposes, either one would work, as we are not doing anything precise with our output. However, any calculations we do will assume a typical NE555 component.

On the bottom right Pin 5 (*Control*) is connected through a $10\ \mu\text{F}$ capacitor to ground. This is just a standard part of using the chip. You can't effectively include capacitors in integrated circuits, so many chips specify certain capacitors be attached to certain pins. The NE555 uses a $10\ \mu\text{F}$ capacitor on Pin 5 to provide voltage stability. In Chapter 18, we learned that capacitors act essentially like little batteries. This capacitor is doing just that. It is providing a short-term supply of charge in case there is a sudden change in current needs within the chip. For instance, when the output goes active, there may be a sudden need for charge. Having this capacitor supplies a quick reservoir of charge available to the chip so that the sudden change in current needs will not affect other chip properties. For most of our uses of the NE555, you can actually leave Pin 5 unconnected—our usage of the chip are not so precise or power-hungry as to be affected in this way. Nonetheless, I show it connected so that you can see how it is *supposed* to be connected.

Down the middle of the schematic is where all of the action happens. This is what controls the oscillation. It is essentially an RC circuit with (a) an extra resistor, and (b) a few tie-ins to the chip. As we will see shortly, the capacitor will alternately charge and discharge. The capacitor itself is attached to two voltage sensors on the chip. The first sensor, *Trigger*, watches the voltage on the capacitor, and activates if the voltage falls below $\frac{1}{3}$ of the supply voltage (the line over the name of the pin indicates that it activates on a low value). The second sensor, *Threshold*, watches the voltage, and will activate if the voltage goes above $\frac{2}{3}$ of the supply voltage.

So, the oscillator works by moving the capacitor voltage back-and-forth between $\frac{1}{3}$ and $\frac{2}{3}$ of the supply voltage. It is fairly obvious to see how the capacitor charges—it is a basic RC circuit using both of the resistors R1 and R2. So how does the capacitor discharge? The capacitor discharges through the action of the *Discharge* pin, Pin 7. When the 555 starts up, Pin 7 essentially acts as if it were not connected to anything, so you can basically ignore it. When the capacitor goes over the $\frac{2}{3}$ supply voltage and triggers the

Figure 19.7: The 555 Oscillator Circuit on a Breadboard



Threshold pin, the 555 will then connect Pin 7 to ground.

Think about what will happen if Pin 7 is connected to ground. Will the capacitor charge? No, the current coming in through R1 will immediately go to ground because it is the easiest path. If the capacitor is charged up, is it above or below ground? It is obviously above ground. Therefore, current will flow *out of* the capacitor, through R2, and to ground. Thus, the capacitor discharges, but at a *different* rate than it charged. The RC circuit for the charging of the capacitor used both R1 and R2 for the resistance. However, the discharge of the capacitor only uses R2. Therefore, the discharge from $\frac{2}{3}$ voltage down to $\frac{1}{3}$ voltage will be faster than the charge up. Once the capacitor discharges down to $\frac{1}{3}$ of supply voltage, Pin 2 (*Trigger*) will detect this event and turn Pin 7 off so that the capacitor can recharge again. Therefore, the capacitor will be continually charging and discharging through $\frac{1}{3}$ to $\frac{2}{3}$ of supply voltage, as the 555 turns Pin 7 (connected to ground) on and off. This is also why having two resistors is so important. If we didn't have R1, when Pin 7 connected to ground it would make a short circuit between the supply voltage and ground.

You may be wondering why there are two detectors connected to the capacitor and not just one. The reason for this is that having two different detectors allows for a *lot* of flexibility in how the 555 is wired. As mentioned earlier, there are a huge number of ways the 555 has been used, and some uses tie *Trigger* and *Threshold* to different parts of the circuit. For our purposes, both of these will always be used together.

So, how does this charging and discharging of the capacitor affect the output? Quite simply, when the capacitor is *charging*, the output is *on*. When the capacitor is *discharging*, the output is *off*. Note that when we first turn on the 555, the output will be on for a little bit longer than for the rest of the time. This is simply because when the circuit first starts up it is charging all the way from 0 V instead of from $\frac{1}{3}$ of supply voltage.

You can see the completed 555 circuit on a breadboard in Figure 19.7. This should blink the light on for about two thirds of a second and off for about a third of a second. This gives the total wavelength of about

1 second, and a frequency of about 1 Hz. In the next section, we'll see how to use RC time constants to calculate our own timings.

19.8 Calculating On and Off Times with the 555

Remember that the capacitor is charging and discharging through an RC circuit. Therefore, we can use what we know about RC circuits to determine how long the circuit will be high and low.

When the capacitor is *charging*, the capacitor is charging through *both* R1 and R2. In this situation, what is the RC time constant? Well, since the resistance is a series resistance, we can simply add them together:

$$\begin{aligned}R_T &= R_1 + R_2 \\&= 50,000 + 50,000 \\&= 100,000\end{aligned}$$

So the resistance is $100,000 \Omega$ and we are using a $10 \mu\text{F}$ capacitor (which is 0.00001 F). Therefore (based on Chapter 19), the RC time constant is $100,000 \cdot 0.00001 = 1$. So our RC time constant is 1 second. However, we are charging/discharging the capacitor in a strange way. We are not starting from zero (except for the first time)—instead we are usually starting from $\frac{1}{3}$ of supply voltage.

Go back to Chapter 19 and look at Figure 19.1. While we don't have a time constant for *exactly* $\frac{1}{3}$ of supply voltage, we do have one for 39.3%, which is pretty close. So, in the table, that occurs as 0.5 time constants. In this case, that is our *starting* value. Our ending value is when the capacitor is $\frac{2}{3}$ charged. That is very close to 63.2%, which is at one time constant. Therefore, the *difference* between the point where we are $\frac{1}{3}$ charged and $\frac{2}{3}$ charged is $1 - 0.5 = 0.5$ time constants.

Since we were using approximate values from the table, this is only an approximation. The circuit actually uses a little longer period than that. It turns out that to go from $\frac{1}{3}$ supply voltage to $\frac{2}{3}$ supply voltage actually takes 0.693 time constants. Since our time constant is 1 second, that makes the calculation really easy: $1 \cdot 0.693 = 0.693$ seconds.

Now, for discharge, remember that the point that it is discharging to is Pin 7. This is *between* R1 and R2. That means that it is *only* using R2 to discharge, so the RC time constant will be based only on R2 and the capacitor. So, the RC time constant is $50,000 \cdot 0.00001 = 0.5$ seconds. Since the charge/discharge time between $\frac{1}{3}$ and $\frac{2}{3}$ is 0.693 time constants, the resulting time to discharge from $\frac{2}{3}$ down to $\frac{1}{3}$ is $0.693 \cdot 0.5 = 0.347$ seconds.

The total wavelength will be the total time for one cycle. This will be our charge time (0.693 seconds) plus the discharge time (0.347 seconds) which will give us a total of 1.04 seconds.

The value 0.693 looks like a strange number, but that will *always* be the value used for the number of time constants for charging/discharging between $\frac{1}{3}$ and $\frac{2}{3}$ of supply voltage. If you are going to use the 555 timer, it is best to just memorize it.

Also note that since the charging goes through *both* resistors while the discharge only goes through *one* resistor, the charge time (with the output on) will *always* be longer than the discharge time (with the output off).

Example 19.17 Let's say we have the basic oscillator circuit shown in Figure 19.6, but with a $2,000\Omega$ resistor for R₁, a $6,000\Omega$ resistor for R₂, and a $10\mu F$ capacitor for C₁. What will be the charge time, the discharge time, the wavelength, and the frequency for our oscillator?

To find this out, it is easiest to first calculate the charge and discharge times separately, and then use those to find wavelength and frequency. The charge time will be calculated based on *both* resistors in our RC circuit. So the resistance will be $2,000\Omega + 6,000\Omega = 8,000\Omega$. The capacitance is $10\mu F = 0.00001F$. This means that the RC time constant will be $8,000\Omega \cdot 0.00001F = 0.08$ seconds.

The number of time constants it takes to charge from $\frac{1}{3}$ to $\frac{2}{3}$ is 0.693. This means that the charge time will be $0.08 * 0.693 = 0.0554$ seconds.

The discharge happens only through R₂. This means that the RC time constant will be $6,000\Omega \cdot 0.00001F = 0.06$ seconds. Since we will use 0.693 time constants, the total time it takes to discharge from $\frac{2}{3}$ down to $\frac{1}{3}$ is $0.693 * 0.06 = 0.0416$ seconds.

Now that we have the charging and discharging times, we find wavelength by merely adding them together. This means the wavelength is $0.0554 + 0.0416 = 0.097$ seconds.

The frequency is merely the reciprocal of this number, or $\frac{1}{0.097}$, which gives us 10.3 Hz.

Example 19.18 Now let's say that we want to build an oscillator for which the LED stays on for 3 seconds and then goes off for 2 seconds. Assuming we keep our $10\mu F$ capacitor, what values should we use for each resistor?

To do this, we need to solve for R₂ first, since it is much easier. The discharge will be 2 seconds, which will be the same as $0.693 \cdot$ time constant. Therefore, we can write this as an equation:

$$\begin{aligned} 2 \text{ seconds} &= R \cdot C \cdot 0.693 \\ 2 \text{ seconds} &= R \cdot 0.00001 \cdot 0.69 \\ 2 \text{ seconds} &= R \cdot 0.0000069 \\ \frac{2 \text{ seconds}}{0.0000069} &= R \\ 289,855\Omega &\approx R \end{aligned}$$

So, the resistor, R₂, needs to be $289,555\Omega$.

The time to charge the capacitor, however, needs to be 3 seconds. This means the resistance (which will be *both* R₁ and R₁) will need to be calculated for this as well. Therefore, we will use a similar equation:

$$\begin{aligned}3 \text{ seconds} &= R \cdot C \cdot 0.693 \\3 \text{ seconds} &= R \cdot 0.00001 \text{ F} \cdot 0.693 \\3 \text{ seconds} &= R \cdot 0.00000693 \\\frac{3 \text{ seconds}}{0.00000693} &= R \\434,783 \Omega &= R\end{aligned}$$

So the resistance for charging the capacitor needs to be $434,783 \Omega$. However, this is the *combined* resistance for R₁ and R₂. Thankfully, though, we already know what we want for R₂— $289,855 \Omega$. Therefore, we can put these into an equation and solve for R₁:

$$\begin{aligned}R_1 + R_2 &= 434,783 \Omega \\R_1 + 289,855 \Omega &= 434,783 \Omega \\R_1 &= 434,783 \Omega - 289,855 \Omega \\R_1 &= 144,928 \Omega\end{aligned}$$

So now we know our values for R₁ and R₂— $144,928 \Omega$ and $289,855 \Omega$. Depending on our application, we would probably simply choose resistors that were close to that amount (like $150 \text{ k}\Omega$ and $300 \text{ k}\Omega$) rather than trying to find a combination of resistors that hit that precise resistance. But, for solving equations, it is best to use exact values.

19.9 Choosing the Capacitor

Review

Apply What You Have Learned

Part V

Amplification Circuits

Chapter 20

Amplifying Power with Transistors

Many devices have limits to the amount of power they can output, or even the amount of power we want them to output. Microcontrollers, for instance, are generally very sensitive with the amount of power they can source. The ATmega328P (used in the Arduino Uno), for instance, has a maximum current rating of 40 mA, which is actually quite generous for a microcontroller. Other types of microcontrollers, such as many PIC microcontrollers, are rated for current outputs of 25 mA or less. Additionally, the voltage is more-or-less fixed at the operating voltage of the chip, which is usually 3–5 V.

However, numerous applications require more power (whether current, voltage, or some combination) than these can output. A typical toy DC motor, for instance, needs about 250 mA for operation. So, if you want to control the motor with a microcontroller, then you have to have some way to convert your small output current into a larger output current to drive your motor.

20.1 An Amplification Parable

As we noted in Chapter 10, physics tells us that we can't actually increase the power of something. What we can do, though, is use a smaller power signal to control a larger power source, and that is what we refer to as amplification.

Let's say that we have a dam on a river. The river wants to go downstream, but it is blocked by the dam. Let's say that we have a giant named Andre, which is able to lift the dam using his strength. If Andre lifts the dam a little bit, a little bit of water flows. If Andre lifts the dam a lot, all of the water can flow. The power of the water itself is actually more than Andre's power. Therefore, Andre can "amplify" his power by raising and lowering the dam.

Let's say that at the end of the riverbed was a structure than Andre wanted to destroy, but Andre isn't strong enough to do it. However, the river is strong enough to do it. Therefore, rather than try to destroy the structure on his own, Andre decides to raise dam and let the river's power do it.

Note that Andre didn't actually increase the amount of power in the river. Instead, he (a being with lesser power), *controlled* the operation of the river (a higher-powered entity). Thus, he *amplified* the effects of his actions by controlling the higher-powered current.

20.2 Amplifying with Transistors

A very common method of amplifying power output in projects is with **transistors**. The term “transistor” is short for “transconductance varistor,” which means that it is an electrically-controlled variable resistor. In other words, it helps you amplify a signal in your project the same way that the dam allowed Andre to amplify his power. The transistor operates as a controllable electric dam, allowing a lesser-powered electric signal to control a higher-powered electric signal. Another way you can think of it as like an outdoor faucet—the water going through the faucet is controlled by the wheel knob on the top.

There are many different types of transistors, with a wide variety of ways that they work. What they all have in common is that they have three (sometimes four) terminals, and one of the terminals acts as a control valve for the operation of the other two. The faucet can be fully-on, fully-off or somewhere in-between, all based on where the knob is set.

The main ways that the types of transistors differ is in whether it is a voltage knob or a current knob. The transistors operated by current are known as **bipolar junction transistors** (BJTs), and the ones operated by voltage are known as **field effect transistors** (FETs).

BJTs come in two basic forms based on whether the knob is activated by positive current (current going into the transistor's base) or negative current (current coming out of the transistor's base). With an NPN transistor, the knob is activated by positive current, while with a PNP transistor, the knob is activated by negative current.

In this chapter, we will focus on NPN BJT transistors.

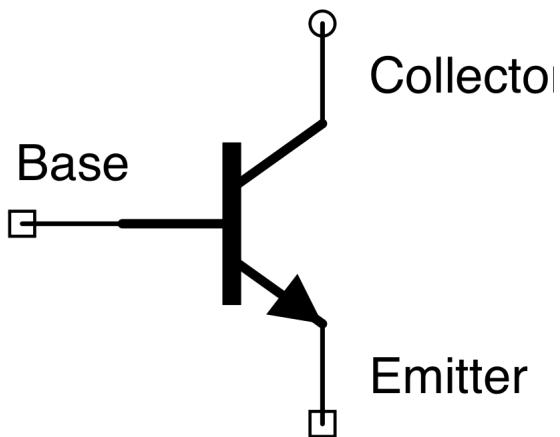
20.3 Parts of the Transistor

A BJT transistor has three terminals—the collector, the base, and the emitter. In BJT NPN transistors small positive current comes in at the base (which you can think of as the knob of a faucet), and it controls the current moving from the collector to the emitter. The more current that exists at the base, the more current is allowed to flow between the collector and the emitter.

Figure 20.1 shows what an NPN BJT transistor looks like in a schematic. The collector is at the top right of this diagram. The emitter is the line with the arrow pointing out. The current being controlled is the current between the collector and the emitter. The base is the horizontal line coming into the middle of the transistor. The base acts as a knob which can limit the flow of current between the collector and emitter.

Figure 20.2 shows a conceptual picture of how the transistor operates. The connection from the base to the emitter operates as a diode, and the connection from the collector to the emitter operates as a variable

Figure 20.1: The Schematic Symbol for a Transistor



resistor, offering resistances from zero (completely open dam) to infinity (completely closed dam).

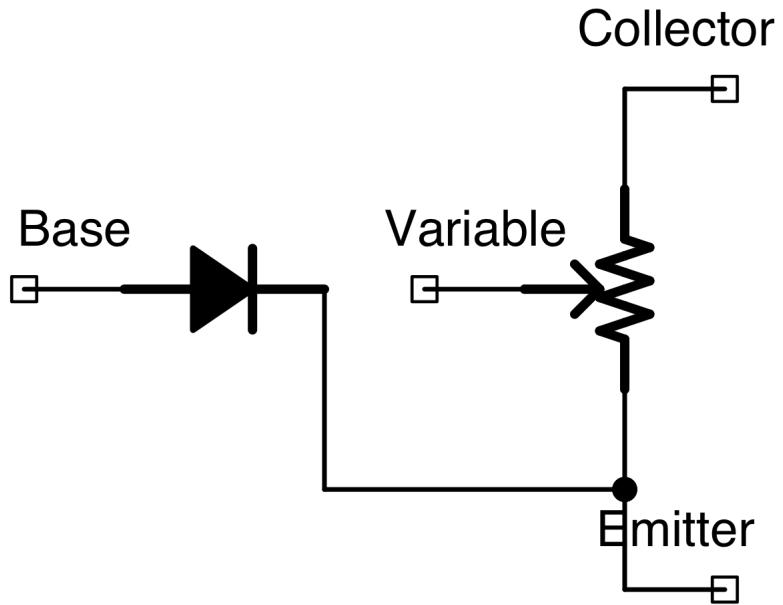
20.4 A Simple Way to Think About the Transistor

To fully understand transistor operation requires a lot of math. However, we are going to first try to understand the basics of what a transistor is doing without using math. To do this, we are going to look at several scenarios, and how the transistor will handle them.

20.4.1 Transistor Off

The easiest thing to envision is the transistor being off. The junction between the base and the emitter operates like a diode, with a 0.6 V voltage drop between them. If the voltage between the base and the emitter (often termed as V_{BE}) is less than 0.6 V, then the base will not conduct and transistor is effectively off. The resistor in Figure 20.2 is basically set to infinity. Therefore, there is no current flowing between either the base or the collector and the emitter.

Figure 20.2: A Conceptual View of Transistor Operation



20.4.2 Transistor Partially On

Once the voltage of the base is high enough, the difference between the base and the emitter voltage will be exactly 0.6 V. Remember, the base-emitter junction acts as a *diode*, and diodes enforce an exact voltage difference. Therefore, whatever the base voltage is, we can expect the emitter voltage to be exactly 0.6 V less.

Once current starts flowing from the base to the emitter, current will also start flowing from the collector to the emitter. The transistor will always maintain the following balance:

- The base-emitter junction will act as a diode, which means that the emitter will be 0.6 V less than the base voltage.
- The collector voltage will be greater or equal to the emitter voltage.
- The transistor will provide appropriate resistance to reduce the voltage from the collector down to the proper voltage on the emitter.
- The transistor can alter current flow on either the base or the collector to maintain this balance.

A lot of that can be confusing. The important thing to remember is that the emitter voltage is determined by the *base* (as well as the emitter's own context to some extent), not the collector. Then, the transistor controls current parameters on its inputs to maintain a balance of currents and voltages within itself. The way that these parameters are managed is known as the **Beta** of the transistor.

20.4.3 Transistor On All the Way

Next up we have the idea of the transistor being on all the way. For this to happen, the voltage difference between the collector and emitter must be zero. Remember that the transistor operates as a variable resistor between the collector and emitter. Therefore, if the voltage difference between the collector and emitter is zero, then the transistor is all the way on.

20.5 The Transistor as a Switch

The easiest way to manage a transistor is as an on/off switch. That is, we will use a small amount of current at the base to turn the transistor on and off.

For this setup, it will be easiest to show you the schematic for what this looks like, and then tell you why we set it up this way. **FIXME—not sure what was here**

The base is the horizontal line that comes into the middle.

That knob controls the stream of current going across the other two terminals in the direction of the arrow. The current goes from the base (with no arrow) to the emitter (the side with the arrow). Note that the base current also exits the transistor through the emitter.

20.6 Basics of Transistor Operation

Sometimes it takes a while to wrap your head around the operation of a transistor. However, while it is a bit *strange* it is not actually *difficult*. You can understand most of how a transistor works by looking at a few simple rules.

1. The pathway between the base and the emitter *always always* acts like a diode. That means that we can count on a 0.6 V drop between the base and the emitter. If we know what the base's voltage is, the emitter's voltage will be *exactly* 0.6 V less.
2. If the base voltage does not rise to at least 0.6 V above the emitter, then the transistor *does not conduct*. If the base doesn't have at least 0.6 V, the transistor is off, the faucet is closed, and no electricity goes from the collector or the base to the emitter. The emitter is basically shut off.
3. The collector voltage *must* be greater than the base voltage. If this does not hold, strange things will happen to your circuit (it will start conducting in unexpected directions).
4. Starting when the base is 0.6 V above the emitter, the transistor acts as a variable resistor for the collector. The transistor adjusts its resistance so that the collector current is a multiple (usually 50–100) of the base current. This will likewise affect the output current the same way, as it will have *both* the base and collector current added together. This multiple is known as the **gain** of the transistor, and is often represented as either h_{FE} or β . Note that while the gain (β) is an important value for a transistor, it can usually be quite a range for any given transistor. For instance, on the 2N2222 transistor, this parameter can vary from 35 to 300! Therefore, a good circuit will not depend too closely on a particular value for β . We will look into how to compensate for this in Chapter ??.

Remember that no matter what the current, the emitter *voltage* will always be 0.6 V below what the base voltage is. Therefore, the transistor supplies both a voltage drop and a current boost.

5. When the base voltage is near the collector voltage, the transistor allows current to flow freely from the collector to the emitter without any impedance, almost as if the collector was directly wired to the transmitter.

Using these rules, we can see that, if we use less than 0.6 V, we can turn off the flow entirely between the collector and the emitter. If, on the other hand, the voltage at the base is near the voltage at the collector, it simply turns the flow between the collector and the emitter all the way on.

Therefore, using these properties, we can use a transistor as a switch to turn a higher-power current on and off.

20.7 Using a Transistor as a Switch

So, let's say that we have program running on an ATmega328/P, and, under certain conditions, we want to turn on a motor. So, we choose an output pin to use (we'll say pin 3 just to have an example). Now, on this chip, output pins put out 5 V but their current rating maxes out at 40 mA. Let's say that we were trying to drive a circuit that needed 400 mA.

To do this, we would use a transistor. We would connect pin 3 to the base through a resistor; we would connect a 5 V power supply to the collector; and we would connect the output circuit to the emitter. Now the output pin is supplying a tiny amount of current compared to the collector. Note that, without the resistor on the base, the pin 3 could still be overdriven. The resistor should be chosen so as to not make the pin output more than it can handle in the worst case scenario. Imagine that the pin gets tied directly to ground. How much resistance would you need to keep that pin under its maximum, 40 mA? Using Ohm's law, we just compute:

$$\begin{aligned} R &= V/I \\ &= 5 \text{ V}/0.040 \text{ A} \\ &= 125 \Omega \end{aligned}$$

If we wanted to be even safer (since the board itself has a maximum total), we could calculate for an even lower maximum. Just remember that, when multiplied by the gain (β) of the transistor, we need to have enough current to run our circuit.

20.8 Analyzing Transistor Circuits

Because of the strange way that transistor circuits operate, analyzing them is a little confusing. However, if you keep in mind some basic rules, it will make analyzing simple transistor circuits like the ones in this book fairly straightforward.

The first step in analyzing a transistor circuit is to figure out what all of the *fixed* values on the circuit are. For instance, are there any diodes forcing a specific voltage drop? What is tied to a voltage source (guaranteeing a fixed voltage) and what is tied to ground (guaranteeing a zero voltage)? For *any* circuit, finding these fixed points is a good start.

The next step is to pretend that the collector is not present.

Part VI

Other Circuits

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.

anode

cathode

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 6.242×10^{18} 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

Appendix E

Integrated Circuit Naming Conventions

The naming conventions for ICs can be bewildering at first. In truth, there is no official standard for chip names, but there are some conventions that are often followed. When a chip is invented, the company that invented it assigns it a part number. However, the courts have ruled that part numbers cannot be copyrighted. Therefore, if another manufacturer makes a similar or identical chip with the same pinout, they will often use the same part number.

E.1 Logic Chip Basic Conventions

Logic chips are often broken up into two families based on the voltage levels that they expect and produce. **TTL** (which stands for transistor-to-transistor logic) and an old standard for logic chips which usually operate at 5 V. TTL chips consider a signal to be “false” when it is below 0.8 V and “true” when it is above 2.2 V, and can break if they receive voltages significantly higher than 5 V. Between 0.8 V and 2.2 V is a region where the resulting value is unpredictable. TTL originally referred to *how* the logic chips were constructed, but now it usually refers to the expected input/output levels of the chip.

CMOS is a newer technology, and with it came a newer standard for how logic levels are interpreted. CMOS chips support a much wider supply voltage range than TTL, but their logic levels are a little different. For CMOS, false is from 0 V to one-third of the supply voltage (whatever it is—CMOS can usually operate from 3 V to 15 V), and true is from two-thirds of the supply voltage to the full supply voltage.

Chips are often made in a series—a whole set of chips which all perform complementary functions. The most common series of logic chips is the 7400 series originally designed by Texas Instruments. The 7400 series started as a set of TTL chips. Some common chips in this series is the 7400 itself (a quad NAND gate), the 7408 (a quad AND gate), and the 7432 (a quad NOR gate).

Chips names will often have a prefix that relates to either their manufacturer or the company that originally designed them. As some examples, National Semiconductor chips are usually prefixed with LM, Texas

Instruments chips have a whole slew of prefixes, including SN and TI, Motorola chips usually have an MC prefix, and Signetics usually has an NE prefix. There are many others, but this is just to give you an example. The 7400 series usually has part numbers starting with SN74 because TI built them. So, a SN7408 is an AND gate based on designs by TI.

Now, the series is 7400. The last two digits refers to the function and pinout of the chips. That is, in the 7400 series, “08” will refer to quad AND gates which all have the same pin configuration. However, sometimes they will insert letters in-between “74” and “08.” This usually refers to some modification to the electrical characteristics of the chip. For instance, a low-power version of the 7400 series have a “74LS” prefix. So, the “SN74LS08” chip is a version of the 7408 (i.e., has the same pinout and function) that was originally designed by TI (the SN prefix) but is built for lower power consumption (LS).

Then, part numbers often have suffixes as well. Suffixes often refer to some external characteristic of the chip. For instance, in Chapter 11, we mentioned different chip packages, such as DIP and SMD. These different packages will have different suffixes. For the 7400 series, the DIP package is usually suffixed with “P,” so an SN74LS08P is the DIP version of the SN74LS08, and the NS74LS08NSR is an SMD version. You may also have suffixes which are based on temperature, hardiness, and even occasionally electrical output characteristics.

Sometimes, if a different manufacturer builds the same chip, they may change the manufacturer code and use different suffixes. For instance, Texas Instruments sells a SN74HC08P, which is a DIP 7408 which uses CMOS levels up to 6 V (that’s what the HC is for). Essentially the same chip is available from Fairchild, which calls it the MM74HC08N. The MM prefix is one that Fairchild uses, it is the same 74HC08 chip, and, for Fairchild, they use an “N” suffix to designate a DIP chip.

As I mentioned, these are only conventions, not standards, so they don’t always apply. However, they can be helpful, so that you know that if someone specifies a 7432 chip, and you see part numbers that say SN74LS32P, you might be able to determine that this at least has some relationship to the chip you are looking for.

Appendix F

Simplified Datasheets for Common Devices