Electronics for Everybody

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Electronics for Everybody

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—Author

Contents

Chapter 1

Introduction

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

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

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

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

1.1 Working the Examples

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

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

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

1.2 Tools You Will Need

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

Chapter 2

Before We Begin

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

2.1 General Safety Note

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

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

2.2 Safety Guidelines

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

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

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

your electric protection exists in your body.

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

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

2.3 Electrostatic Discharge

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

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

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

2.4 Using Your Multimeter Correctly

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

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

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

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

Part I

Basic Concepts

Chapter 3

Dealing with Units

Before we begin our exploration of electronics, we need to talk about **units of measurement**. A unit of measurement is basically a standard against which we are measuring something. For instance, when measuring the length of something, the units of measurement we usually use are feet or meters. You can also measure length in inches, yards, centimeters, kilometers, miles, etc. Additionally, there are some obscure units of length like furlongs, cubits, leagues, and paces.

Every type of quantity has its own types of units. For instance, we measure time in seconds, minutes, hours, days, weeks, and years. We measure speed in miles per hour, kilometers per hour, meters per second, etc.. We measure mass in pounds, ounces, grams, kilograms, grains, etc. We measure temperature in Farenheit, Celsius, Kelvin, and Rankine.

Units for the same type of quantity can all be converted into each other using the proper formula.

3.1 SI Units

The scientific community has largely agreed upon a single standard of units known as the **International System of Units**, abbreviated as **SI Units**. This is the modern form of the metric system. Because of the large number of unit systems available, the goal of creating the SI standard was to create a single set of units that had a basis in physics and had a standard way of expressing larger and smaller quantities.

The imperial system of volumes illustrates the problem they were trying to solve. In the imperial system, there were gallons. If you divided a gallon into four parts, you would get quarts. If you divided quarts in half, you get pints. If you divided a pint into twentieths, you get ounces.

The imperial system was very confusing. Not only were there an enormous number of units, but they all were divisible by differing amounts. The case was similar for length—twelve inches in a foot, but three feet to a yard, and 1,760 yards in a mile. This was a lot to memorize, and doing the calculations was not easy.

The imperial system does have some benefits (the quantities used in the imperial system match the sizes normally used in human activities—few people order drinks in milliliters), but for doing work which require a lot of calculations and units, the SI system has largely won out. Scientific quantities are almost always expressed in SI units. In engineering it is more of a mix, just as engineering is a mix between scientific inquiry and human usefulness. However, the more technical fields have started with SI units and kept with them.

So, the base units for the SI system for everyday quantities are the following:

- Unit of length—the meter
- Unit of time—the second
- Unit of mass—the gram
- Unit of force—the newton

3.2 Scaling Units

Now, sometimes you are measuring really big quantities and sometimes you are measuring very small quantities. In the imperial system, there are different units altogether to reach a different scale of a quantity. For instance, there are inches for small distances, yards for medium-sized distances, and miles for large distances. There are ounces for small volumes and gallons for larger volumes.

In the SI system, however, there is a uniform standard way of expressing larger and smaller quantities. There are a set of modifiers, known as **unit prefixes**, which can be added to *any unit* to work at a different scale. For example, the prefix *kilo* means thousand. So, while a meter is a unit of length, a kilometer is a unit of length that is 1,000 times as large as a meter. While a gram is a unit of mass, a kilogram is a unit of mass that is 1,000 times the mass of a gram.

It works the other way as well. The prefix *milli* means thousandth, as in $\frac{1}{1000}$. So, while meter is a unit of length, a millimeter is a unit of length that is $\frac{1}{1000}$ of a meter. While a gram is a unit of mass, a microgram is a unit of mass that is $\frac{1}{1000}$ the mass of a gram.

Therefore, by memorizing one single set of prefixes, you can know how to modify all of the units in the SI system. The common prefixes occur at every power of 1,000, as you can see in Figure 3.1.

To convert between a prefixed unit (i.e., kilogram) and a base unit (i.e., gram), we just apply the conversion factor. So, if something weighs 24.32 kilograms, then I could convert that into grams by multiplying by $1,000$—$24.32 \cdot 1000 = 24320$. In other words, 24.32 kilograms is the same as $24,320$ grams.

To move from the base unit to a prefixed unit, you *divide* by the conversion factor. So, if something weighs 35.2 grams, then I could convert that into kilograms by dividing it by $1,000$—$35.2/1000 = 0.0352$. In other words, 35.2 grams is the same as 0.0352 kilograms.

You can also convert between two prefixed units. You simply multiply by the starting prefix and divide by

Figure 3.1: Common SI Prefixes

Conversion Factor	Prefix	Abbreviation	Examples
1,000,000,000,000	tera	T	terameter, terasecond, teragram
1,000,000,000	giga	G	gigameter, gigasecond, gigagram
1,000,000	mega	M	megameter, megasecond, megagram
1,000	kilo	K	kilometer, kilosecond, kilogram
1			meter, second, gram
0.001	milli	m	millimeter, millisecond, milligram
0.000001	micro	µ or u	micrometer, microsecond, microgram
0.000000001	nano	n	nanometer, nanosecond, nanogram
0.000000000001	pico	p	picometer, picosecond, picogram

the target prefix. So, if something weight 220 kilograms and I want to know how many micrograms that is, then I will multiply using the kilo prefix (1,000) and divide by the micro prefix (0.000001):

$$\frac{220 \cdot 1000}{0.000001} = 220000000000$$

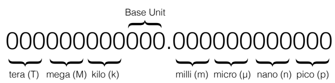
In other words, 220 kilograms is the same as 220,000,000,000 micrograms.

3.3 Using Abbreviations

3.4 Visualizing the Prefixes

You can do everything you need just by knowing the multipliers. However, what usually helps me deal with these multipliers intuitively and instinctively is by simply visualizing where each one lands in a single number. Figure 3.2 shows all of the prefixes laid out in a single number.

Figure 3.2: Visualizing Common Unit Prefixes



Chapter 4

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?

4.1 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 4.1 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 4.1: 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.

4.2 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 $10,000,000,000,000,000,000,000$ electrons (ten thousand billion billion electrons).

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

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

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

Example 4.1 If I were to have 2.3 amps of electricity, how many milliamps is that? To go from amps to milliamps, we multiply by $1,000$. $2.3 * 1,000 = 2,300$. Therefore, 2.3 amps is the same as $2,300$ milliamps.

Example 4.2 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 4.3 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.

4.3 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.

4.4 Which Way Does Current Flow?

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

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

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

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

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

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

Review

In this chapter, we learned:

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

Apply What You Have Learned

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

Chapter 5

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.

5.1 Picturing Voltage

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

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

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

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

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

5.2 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.

5.3 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.

5.4 Resistance

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

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

$$V = I * R \tag{5.1}$$

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

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

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

$$I = V/R \tag{5.2}$$

$$R = V/I \tag{5.3}$$

Equation 5.2 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 5.4 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 5.2. 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 5.5 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 5.3, 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 5.6 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 5.3 to find the resistance we need. $R = V/I = 9/0.010 = 900\Omega$. Therefore, with 900 Ω of resistance, we will limit our current to 10 milliamps.

Review

In this chapter, we learned:

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

Apply What You Have Learned

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

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

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

Chapter 6

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.

6.1 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.

6.2 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 **??**. So, if we want to add 100Ω to our circuit, we just find a resistor with a value of 100Ω. Resistors are not the only devices that add resistance to a circuit, but they are usually what are used when you want to add a fixed amount of resistance. Resistors have two sides, but they both function identically—there is no backwards or forwards for a resistor. You can put them in your circuit either way and they will function just fine.

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

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

Figure 6.1: Wrapping the Resistor around the LED's Short Leg
FIXME—**Need picture here**

6.3 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 6.1.

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!

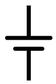
Even though we can't see the electricity moving, I hope you can see how it will flow through the circuit. We can trace the current flow from the positive terminal of the battery through the LED. The resistor limits the amount of current flowing through the circuit, and therefore through our LED (the 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.

6.4 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 6.2: 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.

6.5 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 6.2 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 B.

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

Figure 6.3: Basic LED Circuit Drawn as a Diagram

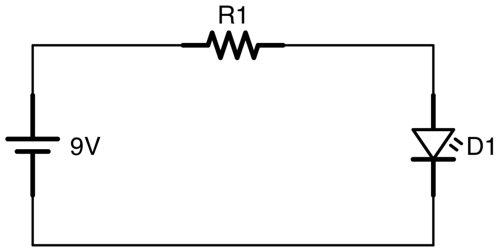
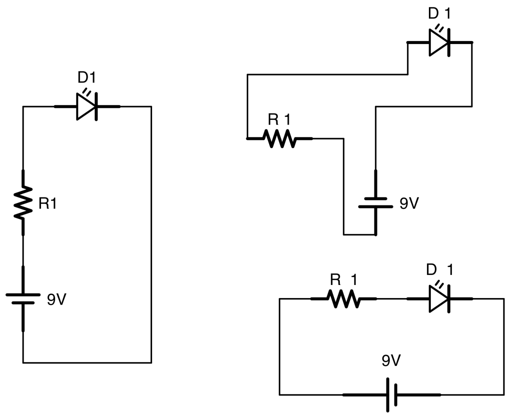


Figure 6.4: Alternative Ways of Drawing the Basic LED Circuit



Therefore, we can redraw our original circuit using these symbols like you see in Figure 6.3.

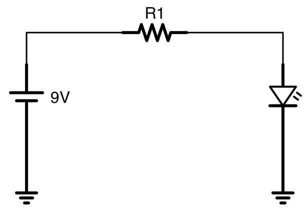
Notice that each of our components are laid out on the diagram with wires connecting them. Remember that it doesn't matter if we have very long wires, very short wires, or if the components are directly placed end-to-end—the resulting circuits will operate identically. Also notice that each component 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 6.4 are equivalent to the circuit in Figure 6.3, 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 6.5: Basic LED Circuit Drawing Using the Ground Symbol



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

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

6.6 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).

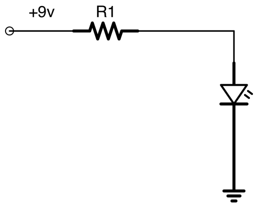
Therefore, the circuit in Figure 6.5 is the same circuit as before, just drawn using the ground symbol. Since every point with the ground symbol are all connected together, using this symbol on both the negative terminal and the negative side of the LED means that they are wired together.

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 6.6. 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 6.6: Simple LED Circuit Using Positive and Ground Symbols



Review

In this chapter, we learned:

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

Apply What You Have Learned

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

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

Chapter 7

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.

7.1 The Solderless Breadboard

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

This was an involved process, and, though it was possible to get your components back, you were generally stuck with your results. The solderless breadboard is an amazing invention that allows us to quickly and easily create and modify circuits without any trouble at all. Figure 7.1 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 7.1: A Solderless Breadboard

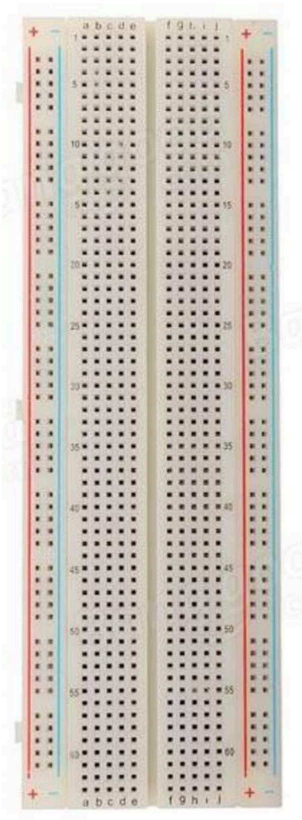
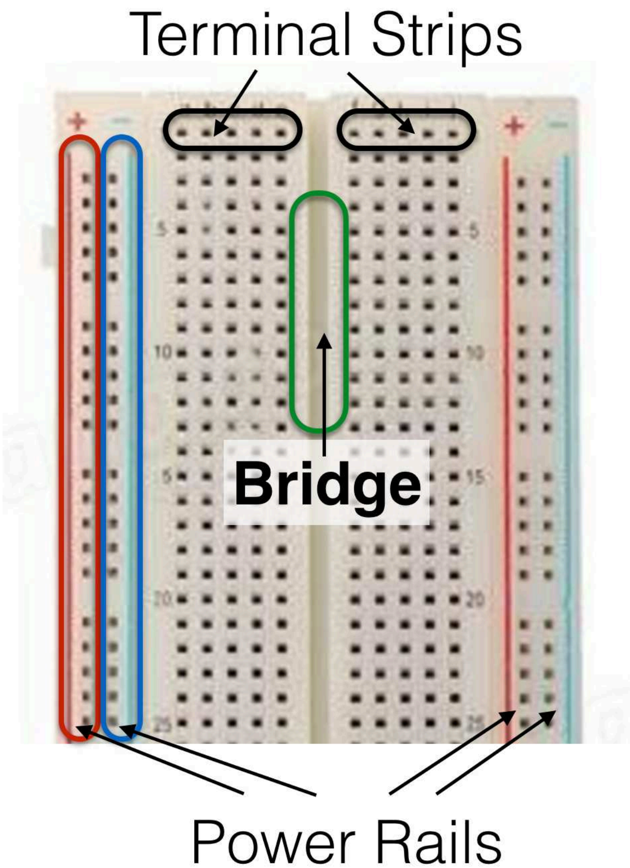


Figure 7.2: Parts of a Solderless Breadboard



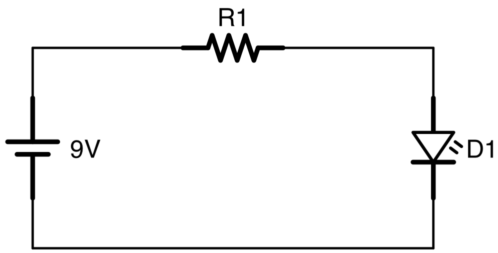
terminal strip are themselves connected.

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 7.3: 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.

7.2 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 6. Figure 7.3 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 7.4 shows how your breadboard should look so far. Note that the longer leg of the LED is closer to the resistor.

Figure 7.5 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 7.4: Putting the Components onto the Breadboard

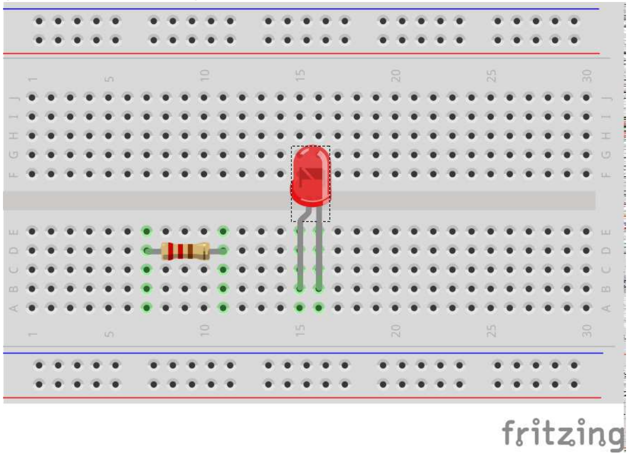


Figure 7.5: The Wrong Way to Put Components onto the Breadboard

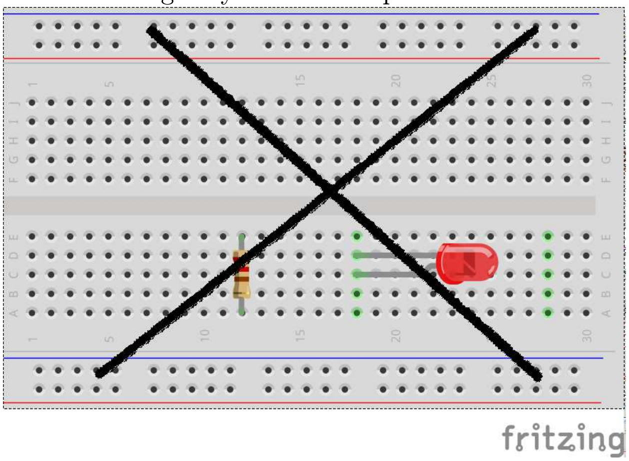
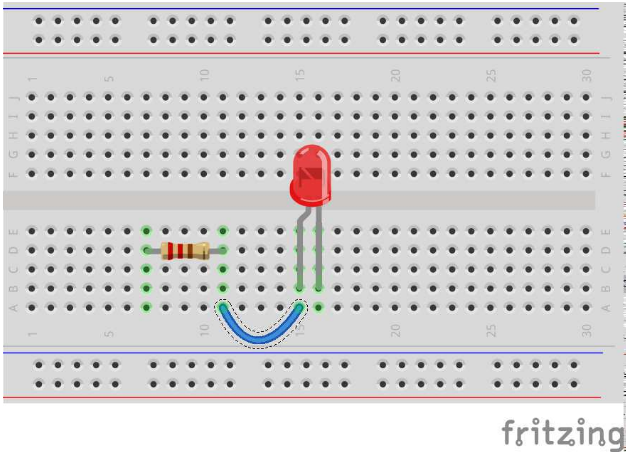


Figure 7.6: Adding a Wire to Connect the Components



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 7.6.

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 7.7.

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 7.8 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 7.7: Adding Wires to the Power Rails

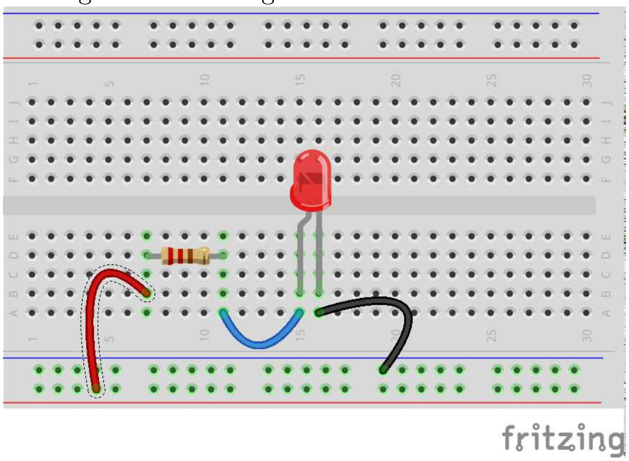


Figure 7.8: Final LED Circuit with Power Connected

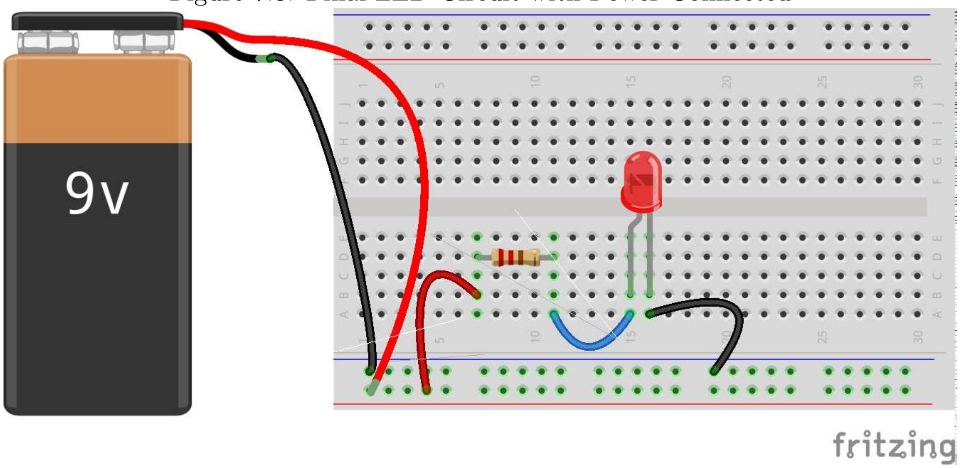
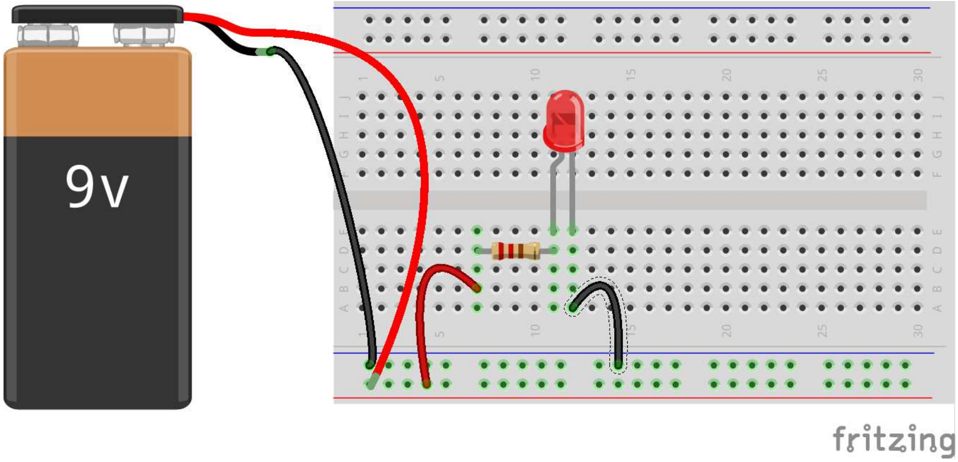


Figure 7.9: Joining Components by Putting Their Leads on the Same Terminal Strip



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.

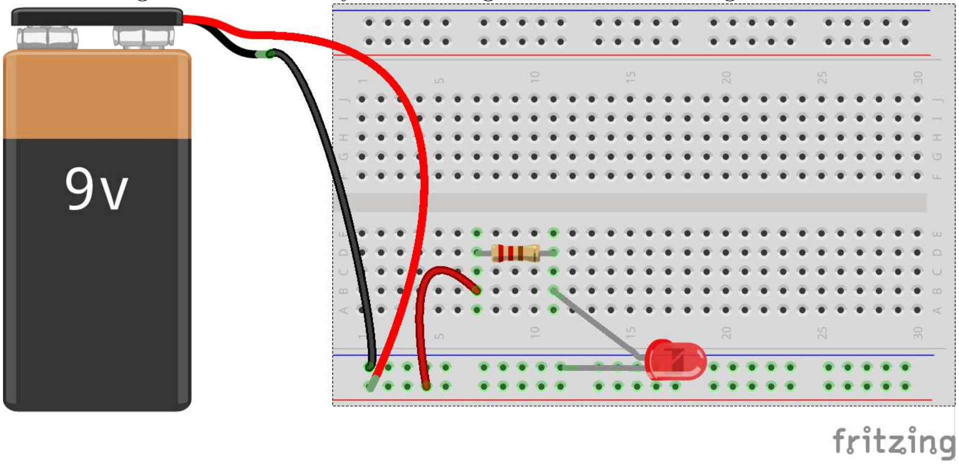
7.3 Using Fewer Wires

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 7.9 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 7.10 shows how this is setup.

Figure 7.10: 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 7.11.

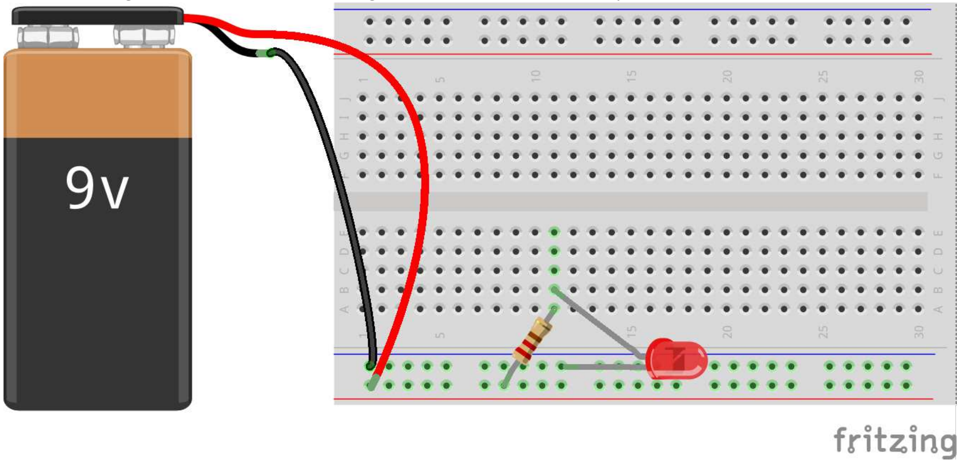
Therefore, as you can see, there are any number of ways that you can arrange parts on a breadboard to match a given schematic. All of these arrangements we have seen match the schematic given in Figure 7.3. As long as your circuit matches the configuration in the schematic, the specifics of where you 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 7.11: Connecting the Resistor Directly to the Positive Rail



7.4 Testing Circuits with a Multimeter

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

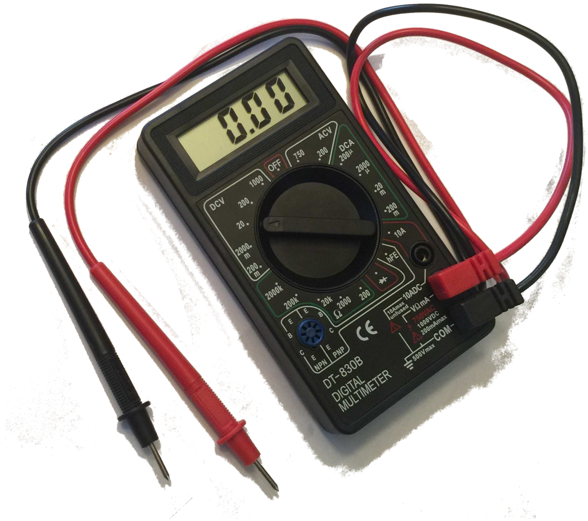
There are a lot of different multimeters around which have a lot of different functions. However, almost all of them will measure voltage, current, and resistance. Each of these values are measured by testing two different points on the circuit. Most multimeters have a red lead and a black lead. The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

To illustrate how to use a multimeter, we will start out measuring the voltage in a 9-volt battery. Remember from Chapter 5 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 7.12: A Low-Cost Multimeter



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

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

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

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

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

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

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

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

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

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

The next thing we will measure is resistance. Pull out a resistor—any resistor. Appendix **??** 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 $0.2\,\mathrm{k}\Omega$, or around $200\,\Omega$. However, this is still not an accurate setting.

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

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

7.5 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 7.8. 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.

7.6 Measuring Current with a Multimeter

Now we will learn to measure current using the same circuit layout from Figure 7.8. 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 destructed in such a way that the components are reusable from one project to the next.
3. Both wire and the legs of a component are attached to connection points on the breadboard.
4. Connection points in the same terminal strip are connected by a wire behind the breadboard.
5. To connect two components together, all you have to do is put their legs on the same terminal strip of the breadboard.
6. The power rails on a breadboard extend 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 7.8. 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 8

Analyzing Series and Parallel Circuits

In the Chapter 6 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.

8.1 Series Circuits

The circuit built in Chapter 6 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 8.1 shows a series circuit with several components included.

Figure 8.1: A Series Circuit with Several Components

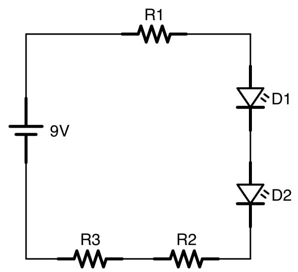
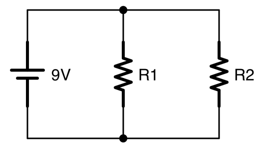


Figure 8.2: Two Resistors Wired in Parallel



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

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

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

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

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

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

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

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

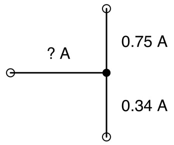
8.2 Parallel Circuits

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

Figure 8.2 shows a simple circuit with two resistors in parallel. In this figure, the circuit has *two* branches. R1 is in the first branch, and R2 is in the second branch. The place where the branch occurs is called a **junction**, and is usually marked with a dot to show that all the wires there are connected.

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

Figure 8.3: 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.

8.2.1 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 8.3 shows a junction where one wire is bringing current in, and it branches with two wires bringing current out. The first wire going out has 0.75 A of current, and the second wire going out has 0.34 A of current. How much current is going into the junction from the left?

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

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

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

Figure 8.4: A Circuit With Many Parallel Paths

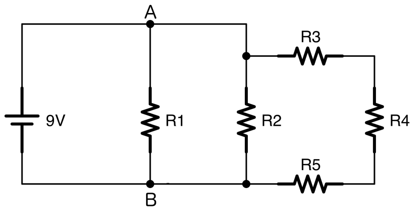
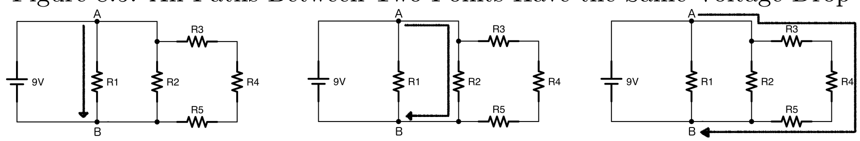


Figure 8.5: All Paths Between Two Points Have the Same Voltage Drop



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

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

8.2.2 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 8.4 and 8.5 illustrates this point. If we wanted to measure the voltage drop between the two points indicated (A and B), then that voltage drop, at least at a particular point in time, will be the same no matter what pathway electricity travels. The direct route between the two points has the same voltage drop as the more winding pathways, no matter what the values of the resistors are.

So how does that square with Ohm's law?

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

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

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

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

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

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 6.4, wires can be considered to be zero-length. Therefore, R2 is just as much directly connected to point A as R1 is. Therefore, the voltage drop across R2 is also going to be 9-volts. Again, using Ohm's law, we can see that

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

So, the current going across R2 is 0.018 A.

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

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

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

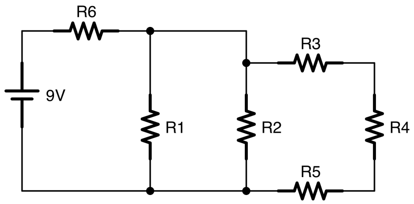
So, using Ohm's law, the current running through this part of the circuit will be:

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

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 8.6: 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.

8.3 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 8.6 gives an example of this. The setup is just like the previous circuit, except there is a single resistor (R6) in series with the battery *before* the parallel branches. This will prevent our simple calculations from working because the current flowing in each of the branches of the circuit will all add together to tell us the amount of current flowing through R6. However, the voltage drop across R6 will depend on the current flowing through it. If this voltage changes, then it will change our starting voltage for our calculations to figure out the parallel branches.

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

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

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \tag{8.1}$$

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

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_N}} \tag{8.2}$$

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 8.2:

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

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

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

$$I = \frac{V}{R}$$
$$I = \frac{9}{522.5}$$
$$I = 0.0172\,\mathrm{A}$$

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:

$$V = I \cdot R$$
$$V = 0.0172 \cdot 250$$
$$V = 4.3\,\mathrm{V}$$

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

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

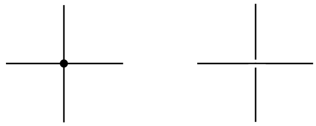
Therefore, we can use Ohm's law to find the amount of current flowing through each of them. For R1:

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

For R2:

$$I = \frac{V}{R}$$
$$I = \frac{4.7}{500}$$
$$I = 0.0094\,\mathrm{A}$$

Figure 8.7: Joined Wires (left) vs. Unjoined Wires (right)



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

$$I = \frac{V}{R}$$
$$I = \frac{4.7}{1500}$$
$$I = 0.0031\,\mathrm{A}$$

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

8.4 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 8.7 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 8.8: Several Points on a Circuit

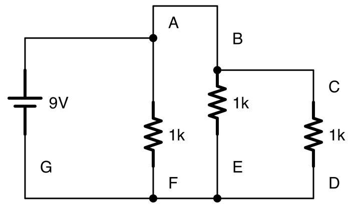
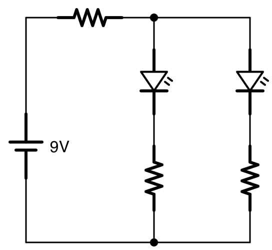


Figure 8.9: A Circuit with Series and Parallel Components



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.

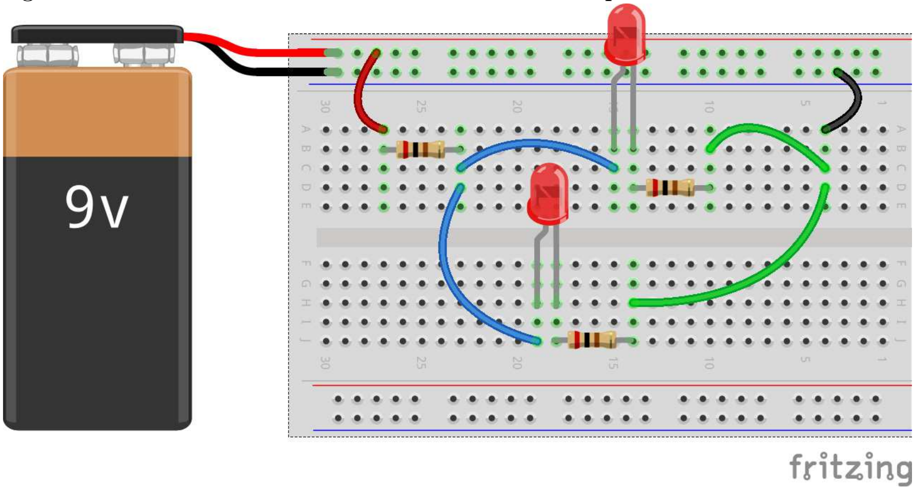
Therefore, in the circuit in Figure 8.8, you can see several points labelled A, B, C, D, E, F, and G. In this circuit, A, B, and C all have equivalent voltages (though not equivalent currents) since there are only wires (and not components) between them. Likewise, D, E, F, and G all have equivalent voltages 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.

8.5 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 8.9 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 200 Ω if you need a specific value (anything between 200 and 1, 000 Ω should work fine).

Figure 8.10: 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 8.10 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 $R_T = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\ldots+\frac{1}{R_N}}$.
8. By using these laws in combination, we can predict how current will flow in each part of our circuit.
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 100 Ω resistors in series, what is the total resistance of the series?

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

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

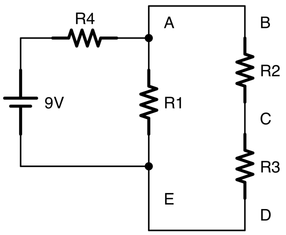
7. If I have two resistors in parallel, a $30\,\Omega$ resistor and a $40\,\Omega$ resistor, what is the total resistance of this circuit?

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

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

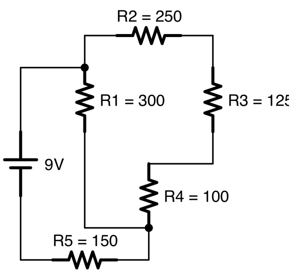
10. If I have three resistors in parallel—$100\,\Omega$, $5,000\,\Omega$, and $10,000\,\Omega$—what is the total resistance of this circuit? Which of the resistors is the total resistance most similar to?

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



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

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



14. Build the circuit in Figure 8.10 on your own breadboard. Measure the voltage drops across every component, and measure the amount of current flowing into the first series resistor.

Chapter 9

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.

9.1 Basic Diode Behavior

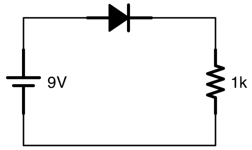
Unlike resistors, diodes have both a positive and negative side. For any component with both positive and negative legs, the positive leg of the component is termed the **anode** and the negative leg is termed the **cathode**. On LEDs, the anode is longer than the cathode. However, for other types of 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 referrig 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 9.1: 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).

9.2 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 9.1. 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:

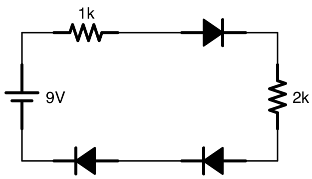
$$I = V/R = 8.4/1000 = 0.0084\,\mathrm{A} = 8.4\,\mathrm{mA}$$

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 9.2 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 $0.6 * 3 = 1.8\,\mathrm{V}$.

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 $9 - 1.8 = 7.2\,\mathrm{V}$ 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 9.2: 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:

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

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 $20 * 0.6 = 12\,\mathrm{V}$. 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.

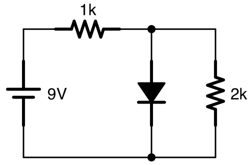
9.3 Circuit Calculations with Diodes in Parallel

The real magic of diodes comes when using them in parallel circuits. Remember the rules that we learned in Chapter 8. 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 9.3 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 resitor 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 9.3: A Single Diode in Parallel with a Resistor



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

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

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 $9 - 0.6 = 8.4$ V. Using this value, we can determine the current going through the resistor using Ohm's Law.

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

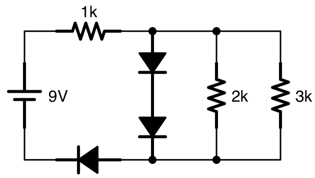
In this circuit, there is 8.4 mA going through the first resistor. That means that there is 8.4 mA coming into the junction. We know that 0.3 mA is going out of the junction through the 2k resistor. That means that the rest of the current is going through the diode. Therefore, we can calculate that the current going through the diode is $8.4 - 0.3 = 8.1$ 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 9.4. 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 9.4: 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 $0.6 * 2 = 1.2\,\mathrm{V}$.

Now we have the parallel resistors to worry about. However, we can use the formula for parallel resistance (Equation 8.2) to figure out the total resistance of the parallel resistors.

$$R_T = \frac{1}{\frac{1}{R1} + \frac{1}{R2}} = \frac{1}{\frac{1}{2{,}000} + \frac{1}{3{,}000}} \approx \frac{1}{0.0005 + 0.0003333} = \frac{1}{0.0008333} \approx 1200\,\Omega$$

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:

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

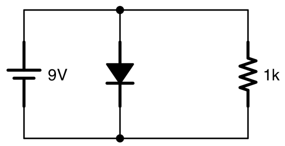
For the 3k resistor, we have:

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

The total current going into both resistors is simple the sum of each of the currents, $0.4 + 0.6 = 1.0\,\mathrm{mA}$. So there is 1 mA 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 $1.2 + 0.6 = 1.8\,\mathrm{V}$. Since the battery is 9 V, that means that there is $9 - 1.8 = 7.2\,\mathrm{V}$ 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 9.5: A Bad Diode Circuit



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

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.

9.4 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 9.5. 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.

9.5 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 9.6 shows an example of this.

Figure 9.6: Nonconducting Diodes

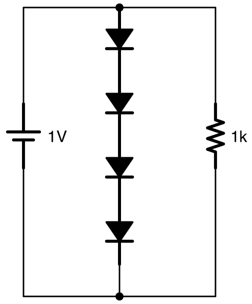
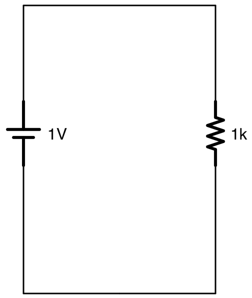


Figure 9.7: A Circuit Equivalent to Figure 9.6 Because of Nonconducting Diodes



In this figure, the voltage drop across the center diode bridge is $0.6 + 0.6 + 0.6 + 0.6 = 2.4\,\mathrm{V}$. However, the battery source is only $1\,\mathrm{V}$. 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 $0.00000022\,\mathrm{mA}$ in this case), but we can think of this circuit as effectively switched off.

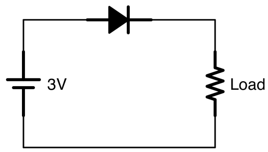
So keep that in mind—if you ever wind up with more forward voltage drop from a diode than you have available voltage, you may treat the diode as if it were an open (i.e., unconnected) circuit—as if it were not even there.

Therefore, we would analyze Figure 9.6 as if it were just like Figure 9.7.

9.6 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 9.8: 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 9.8 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 7, 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.

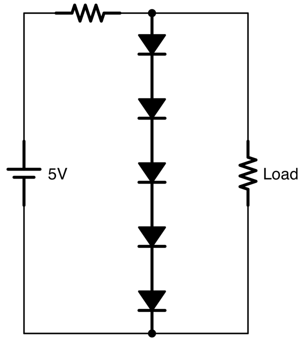
Therefore, if you need a fixed amount of voltage, you can use diodes to provide that at the cost of some extra current.

Figure 9.9 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 9.9: 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:

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

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, $20\,\Omega$ resistor. The voltage will be $5 - 3 = 2\,\mathrm{V}$.

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

So, if we just used a $20\,\Omega$ 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 $500\,\Omega$ resistor:

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

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 $500\,\Omega$ initial resistor, that means that there is only 1 V extra to drain off, so the current will be:

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

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

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

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

So, here, the 20 Ω 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:

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

Therefore, for this situation, the initial resistor should be 286 Ω. 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).

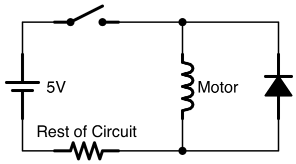
$$I = V/R = 2\,\mathrm{V}/286\,\Omega \approx 0.007\,\mathrm{A} = 7\,\mathrm{mA}$$

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 ±10% variance in the voltage drop of a diode.

Figure 9.10: A Diode Protection Circuit



9.7 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 9.10 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.

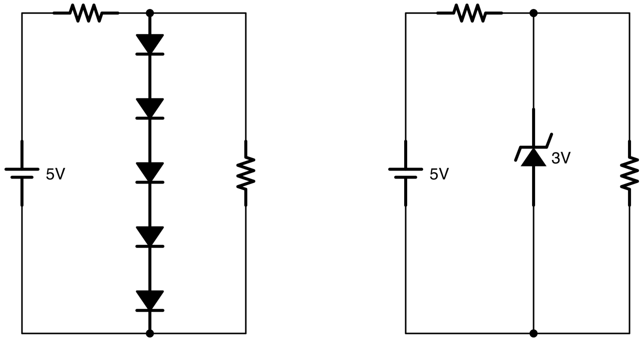
9.8 Zener Diodes

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 9.11 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 9.11: The Zener Diode Schematic Symbol

Figure 9.12: 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 9.12 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

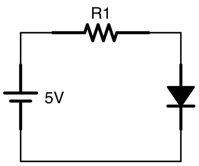
1. If you have a 9 V voltage source, a blue LED, and a 500 Ω resistor all in series, how much current is running through the LED?

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 200 Ω resistor all in series, how much current is running through the LEDs?

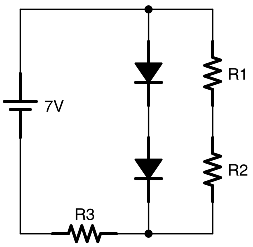
4. If I have a 12 V voltage source, a blue LED, and a red LED, and the LEDs have a maximum current of 30 mA before it breaks and a minimum current of 1 mA before it turns on, what range of resistors can I put in series with the LEDs to get them to light up without breaking?

5. In the circuit below, calculate the how much current flowing through each component and each component's voltage drop if R1 is 500 Ω.



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 R1 is 300 Ω, R2 is 400 Ω, and R3 is 500 Ω.



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 $500\,\Omega$ and operates with a battery voltage from $7\,\mathrm{V}$ to $9.6\,\mathrm{V}$. 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 10

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.

10.1 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 10.1: Schematic Symbols for an SPST Switch (left) and an APST button (right)

Figure 10.2: A Simple Switch Circuit

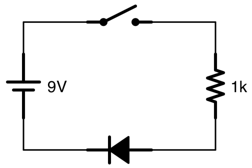


Figure 10.3: A Circuit with Multiple Switches

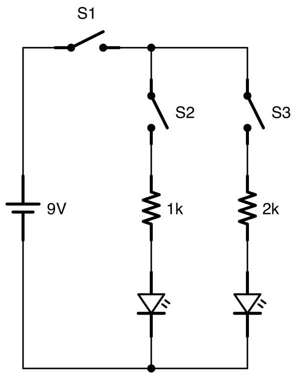


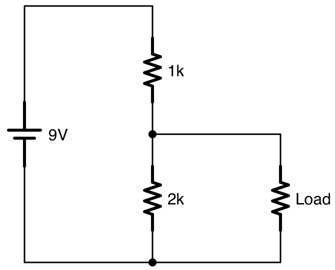
Figure 10.1 show what the schematic symbols for an SPST switch and an SPST momentary switch (i.e., a button) look like. As the drawing indicates, when the switch is open, the circuit disconnects. When the switch closes, it connects the circuit. While the switch holds its position stable (someone has 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 10.2 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 10.3, 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 10.4: A Simple Voltage Divider Circuit



10.2 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 9, we used a resistor to limit the amount of current flowing through our voltage regulation circuit.

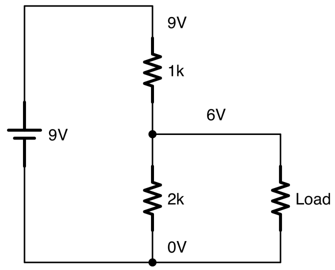
In many different circuits, we will need resistors to limit current for two different reasons—to avoid breaking equipment and to save battery life. Oftentimes, we are actually choosing resistor values to accomplish both of these tasks.

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 400mAh. So, with such a battery, an LED circuit at 10 mA will drain the battery in 40 hours (400mAh/10 mA = 40h), but the same LED circuit with a bigger resistor, limiting the current to 1 mA will take a full 400 hours (400mAh/1 mA = 400h) to drain the same battery! That will save you a lot of money in the long run.

10.3 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 10.4. 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 10.5: 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:

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

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:

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

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 10.5 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:

$$V_{OUT} = V_{IN} * \frac{R_2}{R_1 + R_2} \tag{10.1}$$

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 8.2 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 10.5. 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 $4,000\,\Omega$:

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

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 $20,000\,\Omega$. 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 12 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.

10.4 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 12. It is probably easiest to describe by simply showing you a circuit and then describing how it works.

Figure 10.6 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 10.6: Basic Pull-Up Resistor

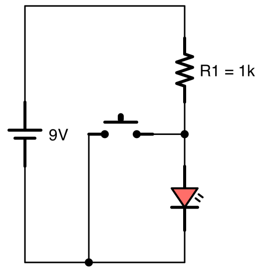
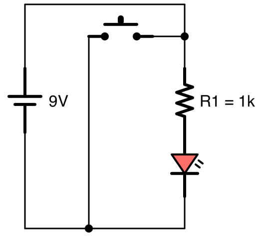


Figure 10.7: Incorrect Way to Wire the Circuit



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 10.7 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).

10.5 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 13. 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 10.3, 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 10.3 (you may swap out resistors with different but similar values—anything from 300 Ω to about 5 kΩ 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 kΩ.
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 kΩ.
6. In Figure 10.6, 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 10.6 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 11

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 capabilties 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.

11.1 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.

11.2 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:

$$P = V \cdot I \tag{11.1}$$

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 milliamps to amps first!):

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

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:

$$V = I \cdot R \tag{11.2}$$

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:

$$P = (I \cdot R) \cdot I \tag{11.3}$$

Or, we can simplify it further and say that

$$P = I^2 \cdot R \tag{11.4}$$

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

$$P = V^2/R \tag{11.5}$$

So, if we have 15 mA running through a 200 Ω resistor, then we can calculate the amount of power being used using Equation 11.4:

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

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 W and 1/2 W (most that I've seen for sale are 1/4 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 11.1:

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 350 Ω of resistance on the *whole* circuit, and have the entire voltage drop occur on the resistor.

11.3 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 13.

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 11.1 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.

11.4 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 weremember 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 11.2, 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 possiblities are.

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

11.5 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?

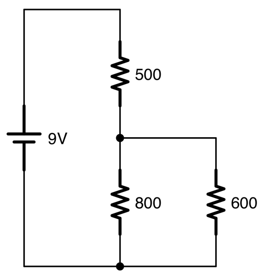
5. If a resistor has a 2 V drop with a 0.03 A current, how much power is the resistor dissipating?

6. If a resistor has a 3 V drop with a 12 mA current, how much power is the resistor dissipating?

7. If a 700 Ω resistor has a 5 V drop, how much power is the resistor dissipating?

8. If a 500 Ω 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 and Microcontrollers

Chapter 12

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 **IC**s. 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.

12.1 The Parts of an Integrated Circuit

Integrated circuits, as we have noted, are basically miniaturized circuits placed on a siliconplate, 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 12.1: Comparison of the Same IC in SMD (left) and DIP (right) Packages

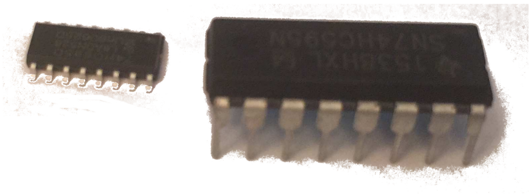


Figure 12.2: Pin 1 is Immediately Counterclockwise of the Notch

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. This 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 12.2 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 12.3 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 12.3: A DIP IC Inserted Into a Breadboard

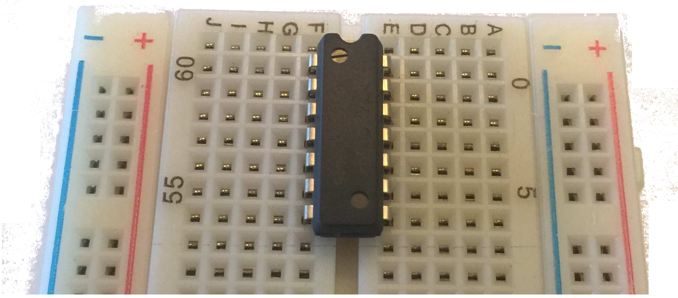
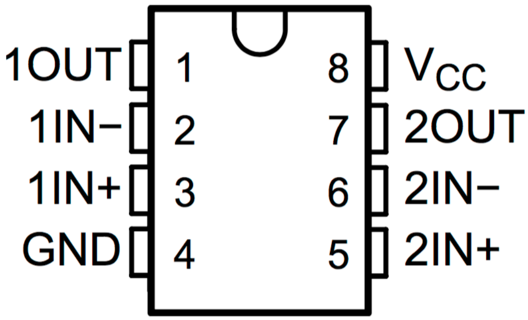


Figure 12.4: The Pin Configuration of an LM393



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.

12.2 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 12.4 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_EE, 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.

12.3 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 D 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.

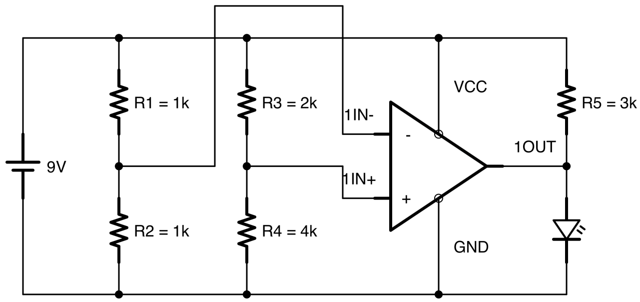
That isn't to say that the datasheets aren't important, but for a beginner the datasheets usually aren't what you need to get started.

12.4 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 10.

The circuit we are discussing is shown in Figure 12.5. 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 12.5: 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 12.4 so they would be easy to locate.

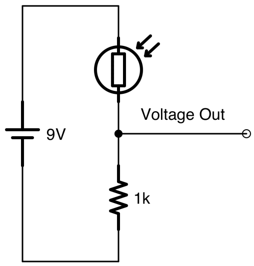
The way that the circuit works is very simple. The voltage coming in to `1IN+` is 6 V and the voltage coming in to `1IN-` is 4.5 V. Since `1IN+` is greater than `1IN-` then that will turn `1OUT` to high (positive voltage). However, remember that we said that `1OUT` *does not conduct* when it is high. 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 10.4. 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 kΩ resistor, we limit the current for the closed switch to $I = V/R = 9/3,000 = 0.003A = 3\,\text{mA}$.

Figure 12.6: 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 $I = V/R = (9 - 1.8)/3,000 = 7.2/3,000 = 0.0024\,\text{A} = 2.4\,\text{mA}$.

12.5 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 12.6 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.

12.6 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 12.5 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 kΩ. Therefore, I am going to use a 15 kΩ 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 kΩ, 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 `1OUT` 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 `1OUT` to high (i.e., opening the switch and allowing power to flow through the LED).

The final circuit is given in Figure 12.7. You can see a way to lay it out on the breadboard in Figure 12.8.

12.7 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 12.7: Darkness Sensor Schematic

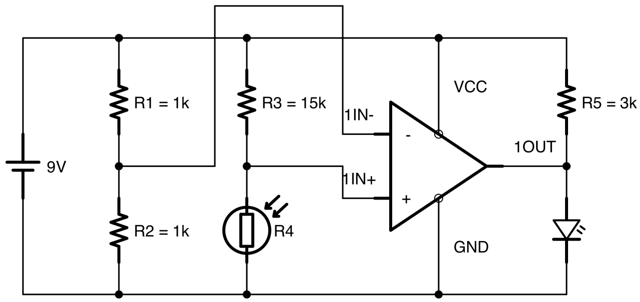
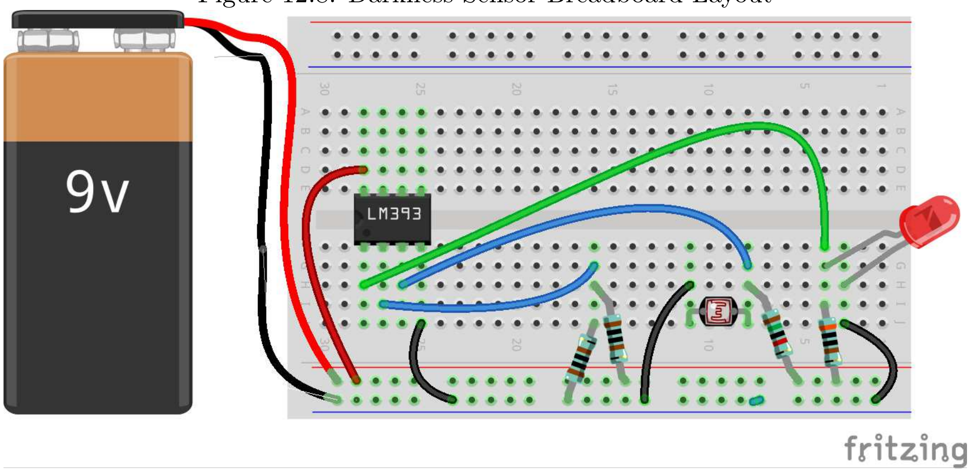


Figure 12.8: Darkness Sensor Breadboard Layout



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 (billionths 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 an 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 ICs 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 12.5. 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 12.5 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 kΩ. When it is bent, it has resistances of 60 kΩ 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 12.7 and 12.8.

5. If you wanted to wait until the room was even darker before the LED went on, how would you change the circuit?

Chapter 13

Using Logic ICs

In Chapter 12, 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.

13.1 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 a 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 13.1 shows the most common types of logic operations and how they work.

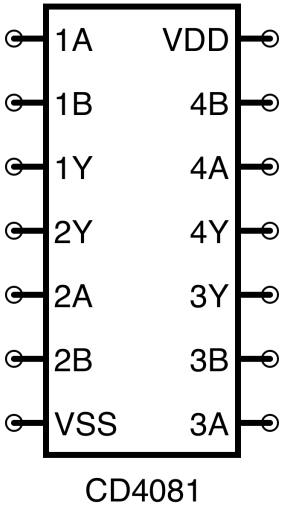
As we have seen, AND yields a true result when both A and B are true and OR yields a true result when either A or B are true. So what are the others? **XOR** is *exclusive OR*, which means that it is just like OR, but is also false when both inputs are true. **NOR** is *not OR*, which means that it is 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 13.1: 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 13.2: The Pinout of a CD4081 Chip



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

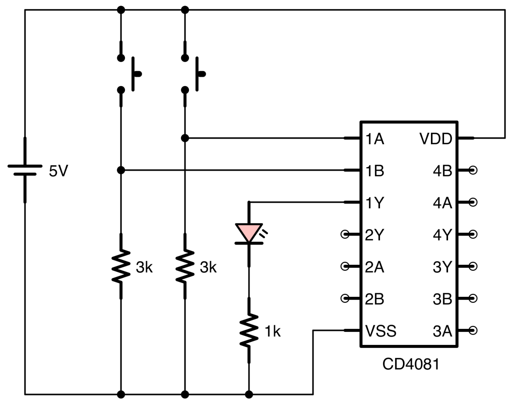
Most logic gates are implemented in chips that contain multiple (often four) implementations of the same gate. For instance, the CD4081 chip is a quad NAND gate chip. The pinout for this chip is shown in Figure 13.2 Note that it has a supply voltage pin (pin 14) as well as a ground pin (pin 7) to supply 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 $3.3\,\text{V}$ or $5\,\text{V}$, 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 $8 - -20\,\text{mA}$, depending on the chip. Because of this, if you use

Figure 13.3: 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 12), 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 13.3 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 13.3.

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.

13.2 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 13.4: A 7805 Voltage Regulator in a To-220 Package

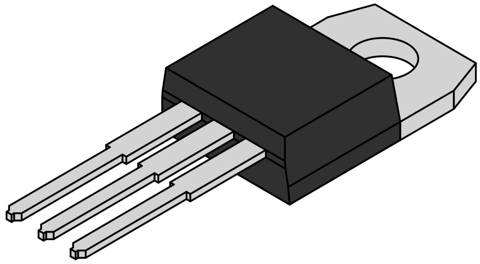
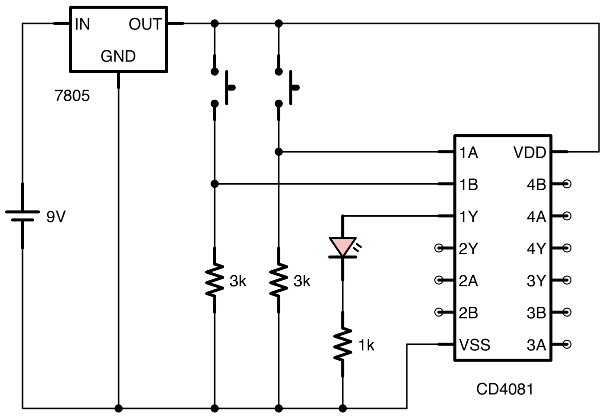


Figure 13.5: Logic Gate Circuit with a Voltage Regulator

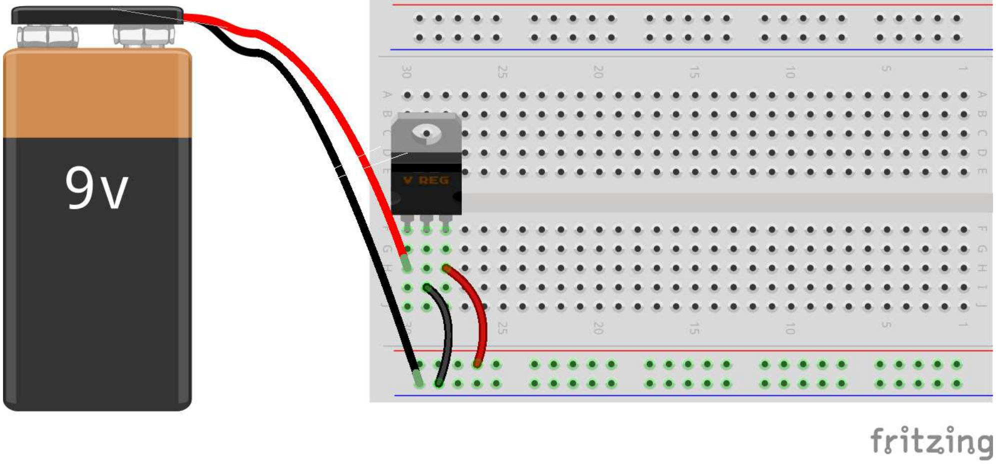


One option is to build a simple 5 V power supply using the knowledge you already have. In Chapter 10 we showed how to build a voltage divider to step down the voltage from a higher voltage source to a lower one. Although not ideal, this could work fine for simple test circuits. A better option would be to build the Zener diode voltage regulator that was shown in Chapter 9 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 13.4. 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 13.5 shows what this looks like in a circuit diagram.

Figure 13.6 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 13.6: 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.

13.3 Pull-Down Resistors

In Figure 13.3, 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 $1\,\mathrm{k\Omega}$ and $10\,\mathrm{k\Omega}$. Beyond $10\,\mathrm{k\Omega}$ the actual function of pulling the voltage down to zero can be slowed down. Additionally, even above $4\,\mathrm{k\Omega}$ it is possible to interfere with the actual logic operation of the chip. Having a resistor below $1\,\mathrm{k\Omega}$, however, means that you are just wasting current.

So, for any button-type input to a digital logic circuit (where the circuit is *phyiscally 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.

13.4 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 13.7 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 13.7: Multiple Logic Gates Combined in a Circuit

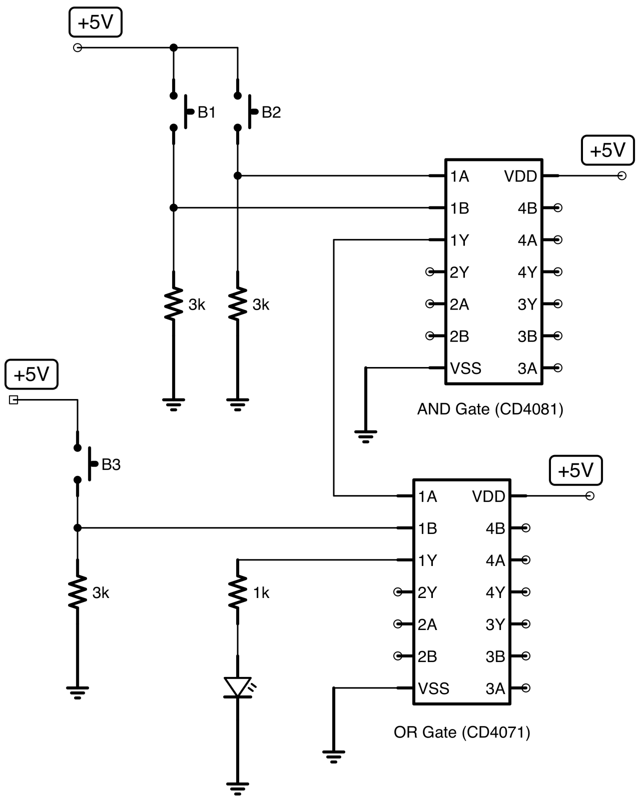
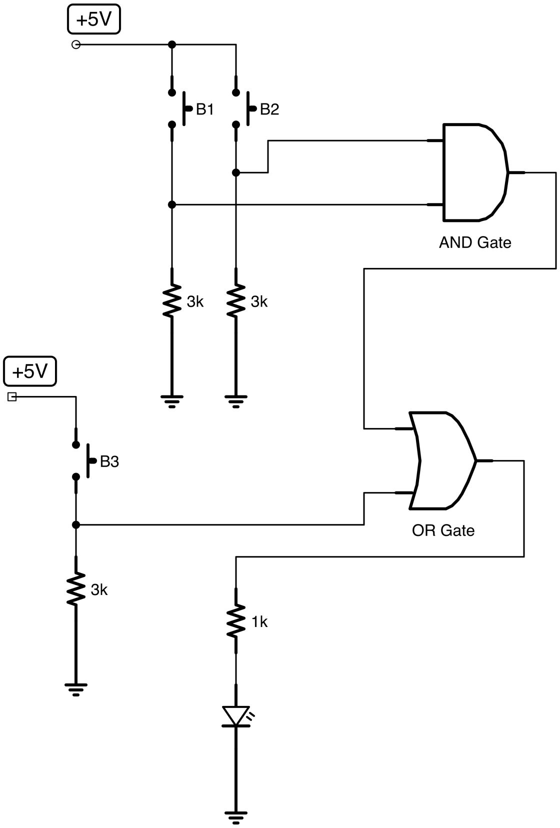


Figure 13.8: Logic Gates Represented as Shapes Instead of IC Pins



This works because, unlike the LM393 (discussed in Chapter 12), 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 13.7. 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 13.8 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 13.9: Common Gates Used in Schematic Drawings

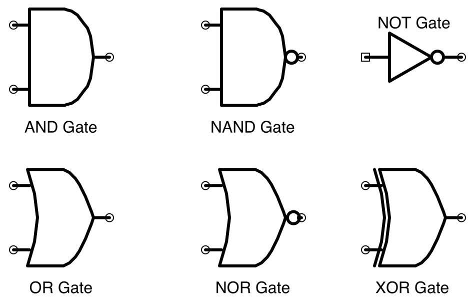


Figure 13.9 shows what these gate drawings look like. The AND gate has a flat back panel and a simple, rounded front. The OR gate looks a bit like a space shuttle, with both the back and the front angled. The NOT gate is a triangle with a circle at the tip. This circle can also be added to other gates 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 13.10 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, if may help you understand why the pins are laid out the way that they are.

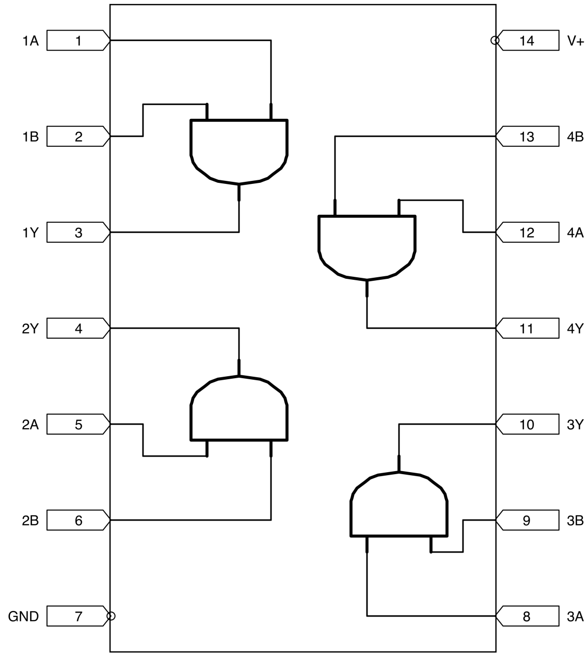
As an interesting side-note, every logic function can actually be built from NAND gates, though you have to wire them up in strange ways. You can actually build a computer entirely from NAND gates if you wanted to. It is not incredibly important, but Figure 13.11 shows how to build each type of logic gate from NAND gates. As an activity, go through the truth tables in Figure 13.1 and see if you can follow how each set of values becomes the result.

13.5 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?

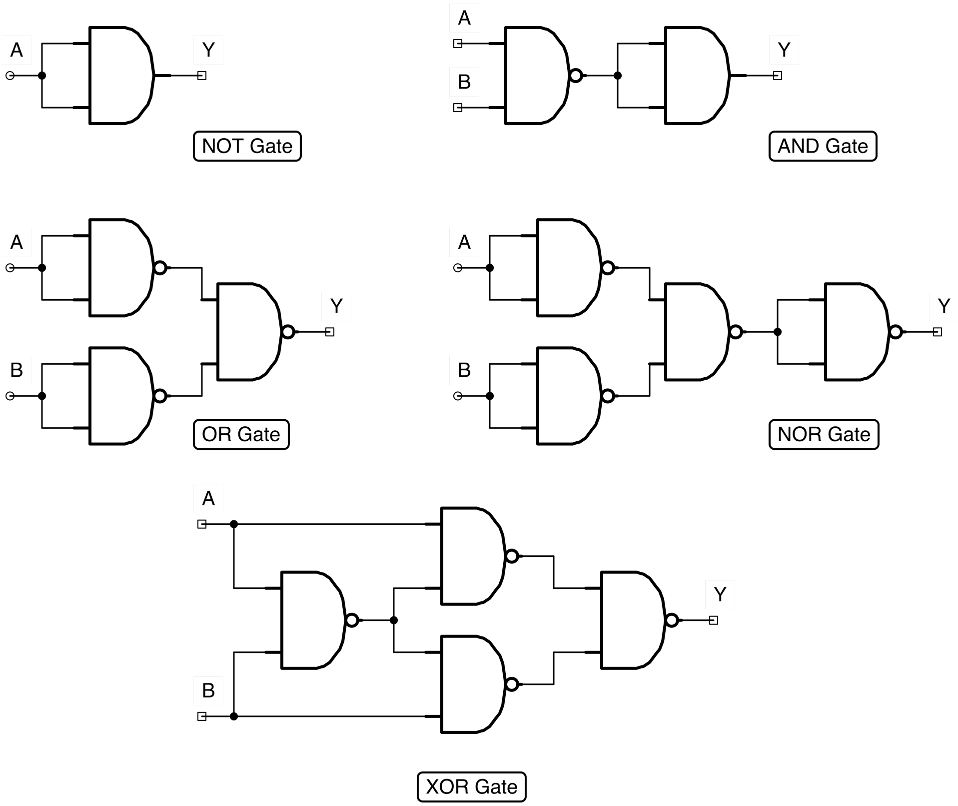
There is a huge selection of chips available, and learning their names is a daunting task. Appendix C attempts to offer some method to the madness, but, at the end of the day, chip names are like people's names—you get to know them by using them. Nobody knows everybody's name, but, for the types of projects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

Figure 13.10: 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 13.11: 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 13.3 yourself. Identify the function of each resistor.
2. Build the circuit in Figure 13.3 (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 13.11. 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 13.1.

10. Take the circuit in Figure 13.3 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 14

Introduction to Microcontrollers

In Chapter 13, 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.

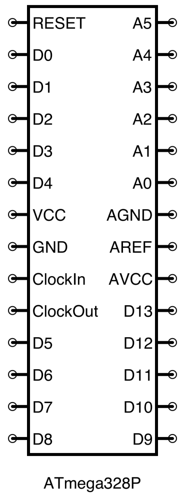
Unlike your typical computer, most microcontrollers can't be connected to a keyboard or other typical input, and can't be connected to a monitor, disk drive, or other typical output. Instead, microcontrollers usually communicate entirely through digital (true/false) electrical signals on their pins.

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.

14.1 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 14.1: 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 14.1 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 14.4.

14.2 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.

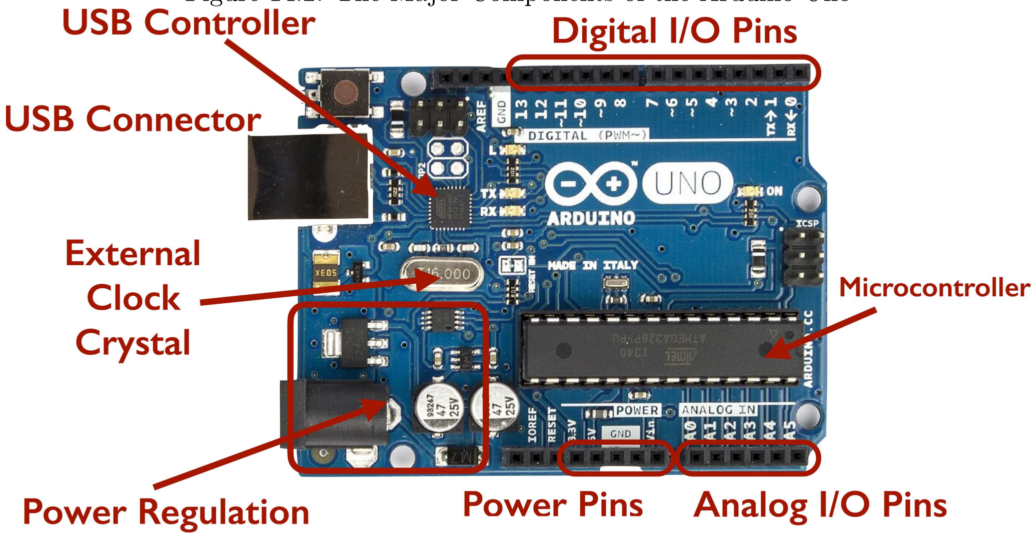
The Arduino environment supports a number of different microcontroller chips. Because it is a simplified environment, many of the special features of individual chips are not directly supported. However, for getting started and doing basic projects, the Arduino environment is excellent.

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.

14.3 The Arduino Uno

This book focuses on the Arduino Uno development board. Figure 14.2 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

Figure 14.2: The Major Components of the Arduino Uno



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.

14.4 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 14.1 (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 15

Building Projects with Arduino

Chapter 14 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.

15.1 Powering Your Breadboard from an Arduino Uno

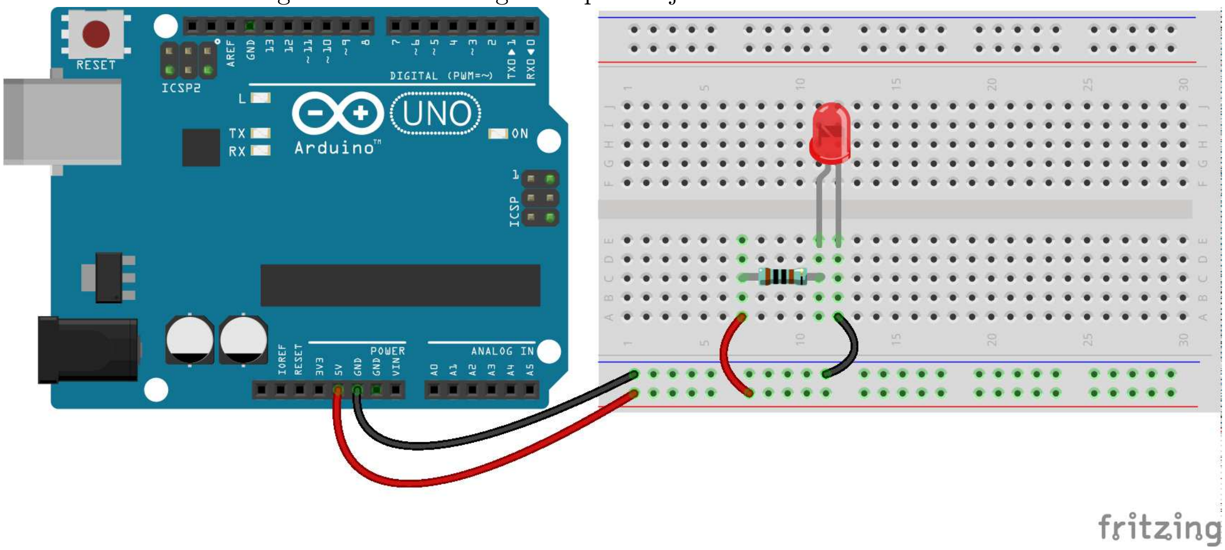
The first thing to understand about the Arduino Uno is that one of its main jobs is power regulation. As we saw in Chapter 14, the Arduino can use a variety of power sources—USB, battery, or a wall plug. Additionally, there is a connection on the Uno's headers that allow for you to supply power from 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. Violà! A very flexible 5 V power supply for your breadboard. Figure 15.1 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 15.1: Powering a Simple Project from an Arduino Uno



15.2 Wiring Inputs and Outputs to an Arduino Uno

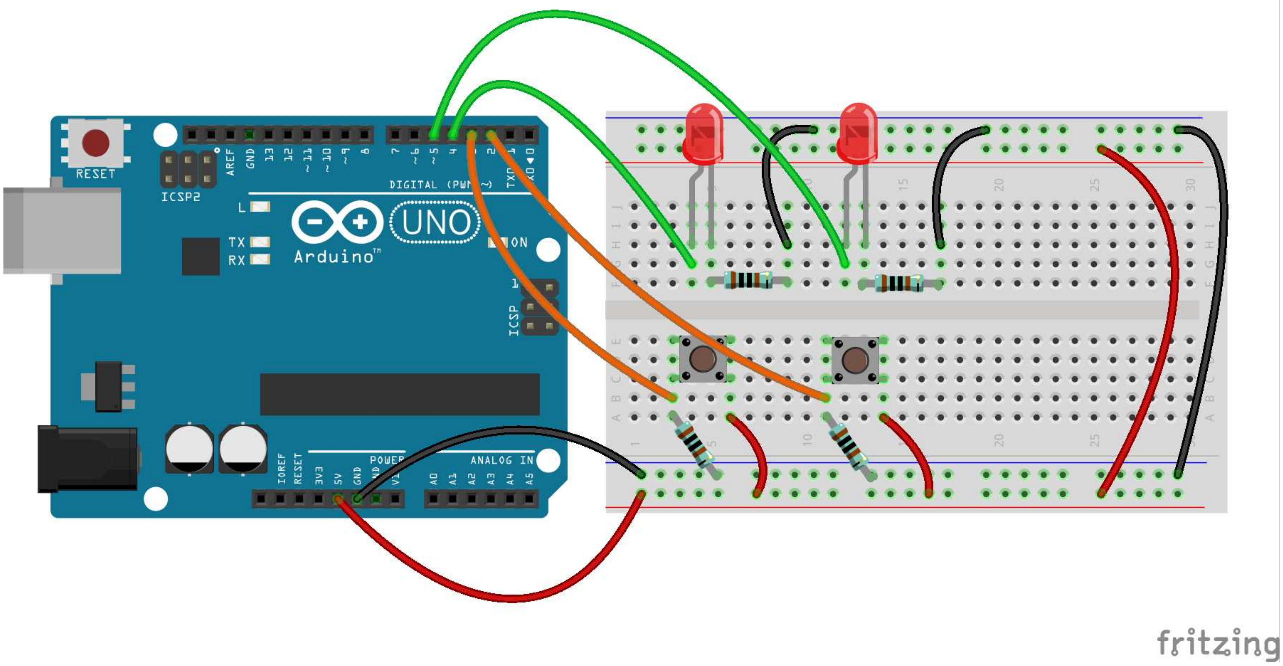
Now that we know how to power a breadboard from an Arduino Uno, we can now see how to connect inputs and outputs to the Uno.

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 MΩ—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 13, 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 15.2: Wiring a Simple Button-based Arduino Project



15.3 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 15.2 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 breadboad. 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 15.3 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 15.3: 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**

15.4 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 `2`s for `3`s 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 16

Analog Input and Output on an Arduino

In Chapter 15, 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.

16.1 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 12 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 16.1 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 16.1: The Darkness Sensor Rebuilt for Arduino

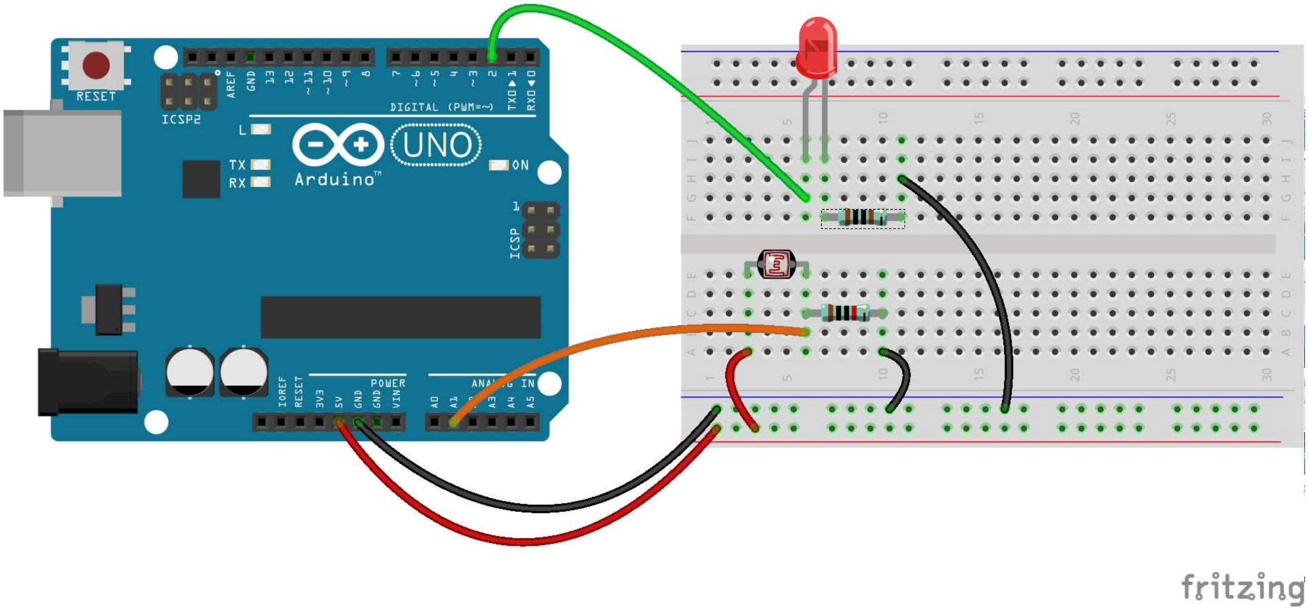


Figure 16.2: Code for the Arduino Darkness Sensor

```
void setup() {
   pinMode(2, OUTPUT);
}

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

Figure 16.2 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 16.3. 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).

16.2 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 16.3: 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 16.4 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 16.5 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 16.4: A Simple Analog Dimmer

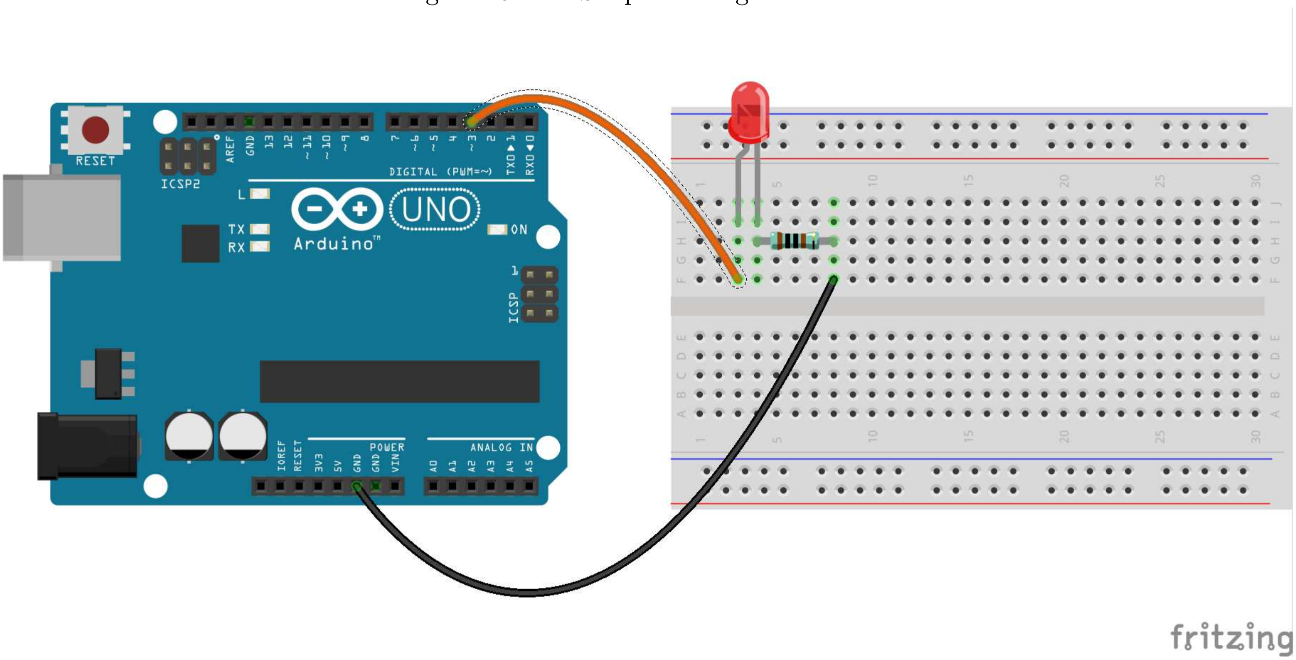


Figure 16.5: Code for the Analog Dimmer

```
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 III

Capacitors and Inductors

Chapter 17

Capacitors

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

17.1 What is a Capacitor?

Before we begin discussing the capacitor, we need to quickly review the concepts from Chapter 4 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 17.1: 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.

17.2 How Capacitors Work

The symbol for a capacitor in a circuit is shown in Figure 17.1. This symbol provides a visual reference for how a capacitor works. Capacitors usually work by having two conductive plates or surfaces that are separated by some sort of non-conductive material. Since the two plates are *near* each other, having a charge on one of the plates will pull charge into the other plate due to the **electric field**. An electric field is generated any time a charge accumulates.

Electric fields influence nearby charges even though they don't directly touch. The field will pull opposite charges closer to itself. Therefore, having a charge will attract the opposite charge in the other plate. However, since the plates 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 plates.

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:

$$Q = C \cdot V \tag{17.1}$$

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

Example 17.7 If I attached a 66 µF 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 µF 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 µF 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:

$$V = \frac{Q}{C} \tag{17.2}$$

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

Example 17.8 If I have a charge of 0.0023 coulombs stored in a 33 µF 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 $33\,\mu\text{F} = 0.000033\,\text{F}$. 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.

17.3 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 17.2. 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).

Figure 17.2: A Polarized Capacitor Symbol

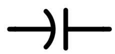
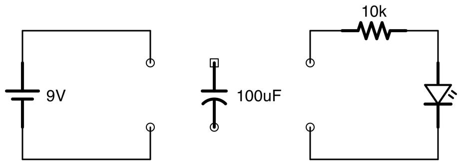


Figure 17.3: Using a Capacitor as a Battery



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 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 $230,000\,\text{pF}$ (23 followed by 4 zeroes). If the number was 230, then the capacitance is $23\,\text{pF}$.

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 (±5%), K (±10%), and M (±20%).

17.4 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 it charged, you can use the capacitor as a very tiny battery for a project.

In Figure 17.3, 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 resitor at least $10\,\text{k}\Omega$. So, first, build the LED circuit on the right side of Figure 17.3 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 $9\,\text{V}$ 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 17.2, 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 17.9 If we used the components listed in Figure 17.3, how much charge does the battery initially store in the capacitor?

We can use Equation 17.1 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 17.10 After 0.0003coulombs of charge have been discharged, what voltage is the caapacitor 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 17.2 to find out what the voltage is that the capacitor is discharging at.

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

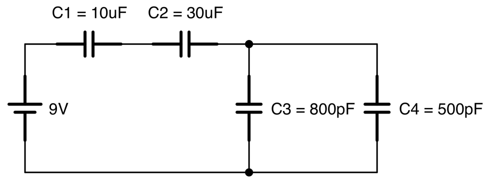
Therefore, the capacitor is discharging at 6 V

17.5 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 17.4: Capacitors in Series and Parallel



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

$$C_T = C_1 + C_2 + \dots \tag{17.3}$$

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

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots} \tag{17.4}$$

Example 17.11 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 17.4. 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 µF. Now, we will plug these values into the equation:

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

Example 17.12 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 17.4. 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, $C_1 = 0.00001\,\mathrm{F}$, $C_2 = 0.00003\,\mathrm{F}$, $C_3 = 0.0000000008\,\mathrm{F}$, and $C_4 = 0.0000000005\,\mathrm{F}$. C3 and C4 are in parallel, so we can combine them using the parallel formula (Equation 17.3:

$$\begin{aligned} C_T &= C_3 + C_4 \\ &= 0.0000000008\,\mathrm{F} + 0.0000000005\,\mathrm{F} \\ &= 0.0000000013\,\mathrm{F} \end{aligned}$$

Now, if we substitute that capacitance in for C3 and C4, we can use the series formula (Equation 17.4) to find the total capacitance of the circuit:

$$\begin{aligned} C_T &= \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_{3\&4}}} \\ &= \frac{1}{\frac{1}{0.00001} + \frac{1}{0.00003} + \frac{1}{0.0000000013}} \\ &= \frac{1}{100000 + 33333.33 + 769230769.23} \\ &= \frac{1}{769364102.56} \\ &= 0.0000000013\,\mathrm{F} \\ &= 1.3\,\mathrm{nF} \end{aligned}$$

So the total capacitance of the circuit is 1.3 nF.

17.6 Capacitors, AC, and DC Currents

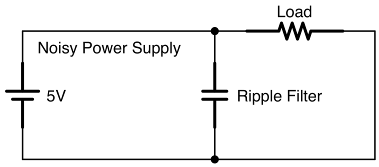
One important characteristic of a capacitor is that they *allow* the flow of AC (alternating current) but they *blocks* the flow of DC (direct current). To understand why this is, let's think about how capacitors operate.

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 17.5: 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.

17.7 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 17.5. 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* and 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 ony allow lower frequencies (the higher frequencies will be shunted to ground).

Review

In this chapter, we learned:

1. An electric field is generated wherever there is an accumulated charge.
2. A capacitor is a device that stores electric energy by holding two opposing charges.
3. Capacitors are sized by their capacitance which is measured in farads.
4. Because a farad is so large, capacitors are usually measured in microfarads, nanofarads, and picofarads.
5. Polarized capacitors (usually electrolytic capacitors) have distinct positive and negative terminals, while non-polarized capacitors (usually ceramic disk capacitors) can go either way.
6. When a battery is connected to a capacitor, it will store a charge on the capacitor.
7. 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.
8. 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: $V = \frac{Q}{C}$.
9. 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.
10. 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.
11. When multiple capacitors are used together, their capacitances can be combined similar to resistors, but with the series and parallel equations switched.
12. Series capacitance equation: $C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots}$
13. Parallel capacitance equation: $C_T = C_1 + C_2 + \ldots$
14. Capacitors allow the flow of AC current through them but block the flow of DC current.
15. 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.
16. 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 µF to farads.
3. Convert 0.0002 F to microfarads.
4. Convert 0.0030 µF to farads.
5. If a voltage of 6 V is applied to a 55 µF 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 µF 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 µF 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 18

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.

18.1 Time Constants

As we learned in Chapter 17, 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 17.1). 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 18.1 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 18.1: 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 18.13 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:

$$\begin{aligned}
\text{RC Time Constant} &= \text{capacitance} \cdot \text{resistance} \\
1.8 &= 0.0001 \cdot R \\
0.0001 \cdot R &= 1.8 \\
R &= \frac{1.8}{0.0001} \\
R &= 18000
\end{aligned}$$

Therefore, to make it take 9 seconds to charge the capacitor, we need to use an 18 kΩ 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 18.1 to be the percentage *discharged* that the capacitor was.

Example 18.14 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 $5\,\mathrm{k\Omega}$ 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.

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

So the RC time constant is 0.5 seconds.

So, after 2 seconds, we have performed 4 RC time constants. Looking at Figure 18.1, we have discharged 98.2% of the capacitor's voltage. This means that the amount of voltage *lost* should be $0.982 \cdot 7\,\mathrm{V} = 6.874\,\mathrm{V}$. If we have lost that much voltage, that means we should subtract it, so the remaining voltage is $7\,\mathrm{V} - 6.874\,\mathrm{V} = 0.126\,\mathrm{V}$.

So the voltage after 2 seconds will be $0.125\,\mathrm{V}$.

18.2 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 12, 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 $5\,\mathrm{V}$ 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 18.1 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.

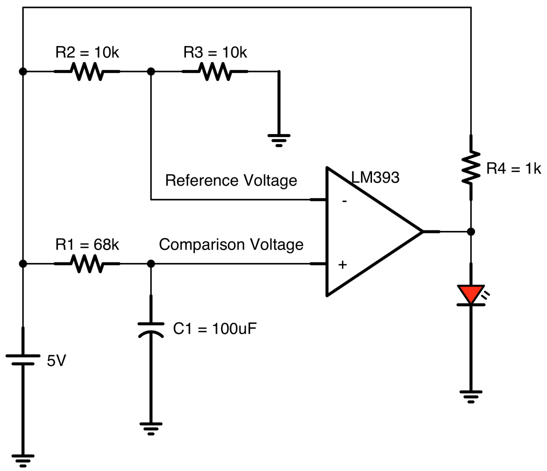
$$\begin{aligned} 7.14 &= R \cdot C \\ 7.14 &= R \cdot 0.0001 \\ \frac{7.14}{0.0001} &= R \\ 71400 &= R \end{aligned}$$

Therefore, we need a resistor that is about $71,400\,\Omega$. 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 $68,000\,\Omega$ (i.e., $68\,\text{k}\Omega$). That is close enough (though I could get even closer by adding in a $3\,\text{k}\Omega$ resistor in series).

Figure 18.2 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 12, 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 18.2: 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 18.3 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 12.4.

Notice the prominence of our basic circuits from Chapter 10. 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.

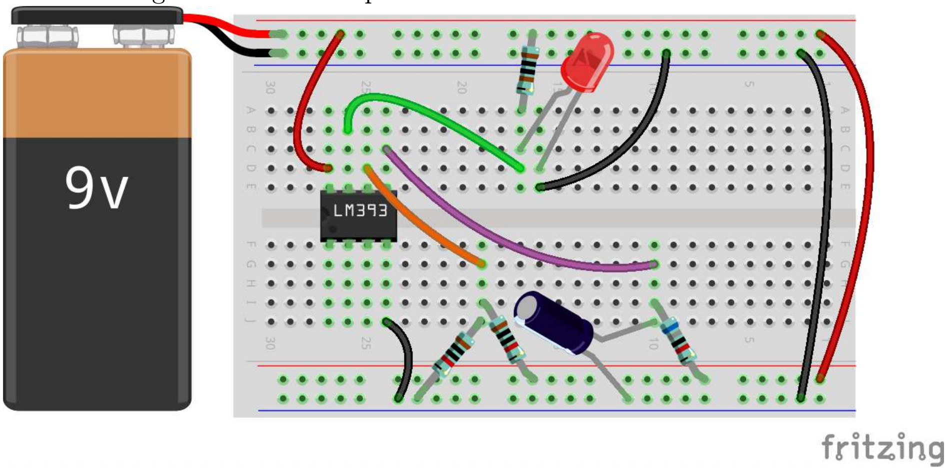
On the bottom right, we have our new timing circuit, which looks a lot like a voltage divider. In fact, it acts like one, too, where the voltage varies by time! If you think about what the capacitor is doing, when we first apply voltage it acts like a short circuit—in other words, no resistance. This 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!

18.3 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 18.3: 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 18.4 shows how to do this.

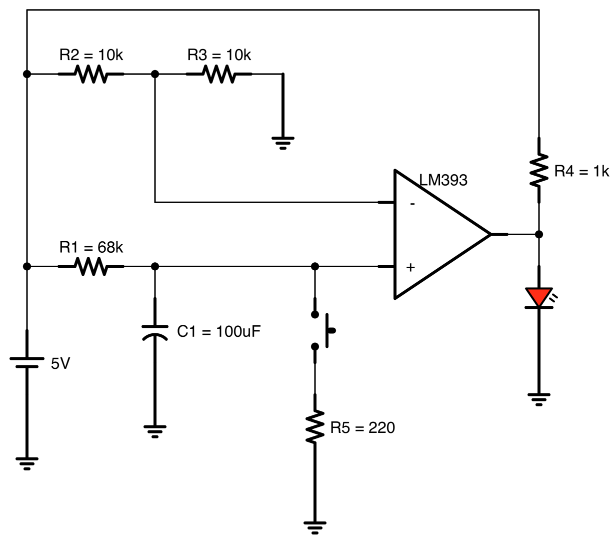
Now let's look at how this circuit works. First of all, we added two components, the switch and the R5 resistor connected to it. To understand what this does, pretend for a minute that the resistor isn't there. What happens when we push the button? That would create a direct link from the positive side 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 18.4: 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 R1 is 68 kΩ and R5 is 200 Ω, what is the voltage at the point of division? If we use a 9 V supply, then using the formula from Equation 10.1 then we can see that:

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

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 18.1 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 18.1 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 10 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 $2\,\text{F}$, 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 $0.001\,\text{F}$, 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 $20\,\mu\text{F}$, 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 18.2 to wait for 3 seconds. Draw the whole circuit.
8. Redraw the previous circuit, and circle each basic circuit pattern and label it.

Chapter 19

Introduction to Oscillator Circuits

In Chapter 18, 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.

19.1 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 18, 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 **period** or its **frequency**. The period 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 period would be three seconds.

The frequency of an oscillation is the number of times that the system cycles every second, which is merely the reciprocal of the period (i.e., one divided by the period). So, in the example given, since the period 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 $\frac{1}{3}$ 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 period and frequency of this oscillator?

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

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

So, what is the frequency of this oscillator? Simple, just take the reciprocal of the period. 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 period of this sound?

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

There are many other factors that are important to various kinds of oscillations, such as the speed of transition between states, what percentage of time each state is achieved, etc. However, the period/frequency is a good way to summarize the behavior of an oscillator into a single number.

19.2 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.

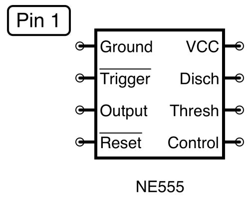
Time clocks Every clock on earth operates by an oscillator. The clock simply counts the number of oscillations that have occurred to know whether or not to advance another minute.

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.

Figure 19.1: The 555 Pinout Diagram



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.

19.3 Building an Oscillator

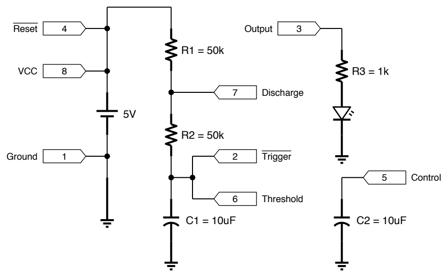
Let's think for a moment of what it would take to build an oscillator. You have at least two different states—on and off. You *can* build an oscillator with more than two states, but we won't be concerned with such things in this book. Then, you have a time period between the two states. What sort of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

As we saw in Chapter 18, 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 called 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 19.2 blinks an LED on and off.

Figure 19.2: A Schematic of a Simple 555 Oscillation Circuit



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 ($\overline{Reset}$) 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. Since most pins are activated by a higher voltage, pins that are activated with a lower voltage get 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.

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 µF 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 µF capacitor on Pin 5 to provide voltage stability. In Chapter 17, 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, $\overline{Trigger}$ 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 $Threshold$ pin, the 555 will then connect Pin 7 to ground.

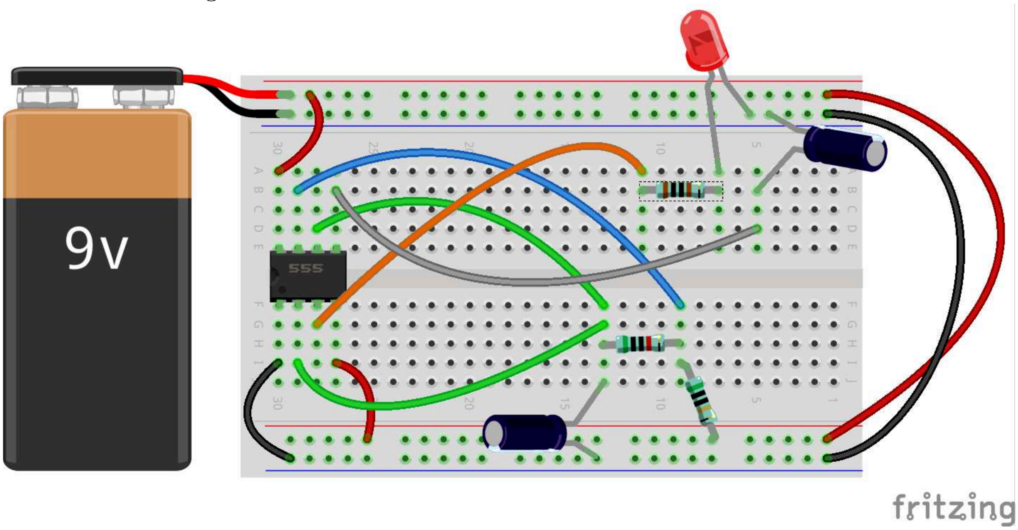
Think about what will happen if Pin 7 is connected to ground. Will the capacitor charge? No, the current coming in through R1 will immediately go to ground because it is the easiest path. If the capacitor is charged up, is it above or below ground? It is obviously above ground. Therefore, current will 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 ($\overline{Trigger}$) 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 $\overline{Trigger}$ 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 19.3. 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 period 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.

Figure 19.3: The 555 Oscillator Circuit on a Breadboard



19.4 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 $0.00001\,\text{F}$). Therefore (based on Chapter 18), 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 18 and look at Figure 18.1. 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 use 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 from $\frac{2}{3}$ down to $\frac{1}{3}$ is $0.693 \cdot 0.5 = 0.347$ seconds.

The total period 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 th 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 19.2, but with a $2,000\,\Omega$ resistor for R1, a $6,000\,\Omega$ resistor for R2, and a $10\,\mu\text{F}$ capacitor for C1. What will be the charge time, the discharge time, the period, 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 period 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 $10\,\mu\text{F} = 0.00001\,\text{F}$. This means that the RC time constant will be $8,000\,\Omega \cdot 0.00001\,\text{F} = 0.08$ 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 $6,000\,\Omega \cdot 0.00001\,\text{F} = 0.06$ 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 the period by merely adding them together. This means the period 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 $10.3\,\text{Hz}$.

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 $10\,\mu\text{F}$ 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 $0.693 \cdot \text{time constant}$. 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.

19.5 Choosing the Capacitor

Ultimately, there are no hard-and-fast rules for choosing capacitors. As long as the RC time constant yields the right value, then you can compensate for pretty much any size capacitor with the right size of resistor.

However, sometimes just having a little guidance helps people get started, and there are a few situations that you need to watch out for.

First of all, the size of capacitor will affect the size of resistor you need for a given time constant. If all you have are smaller-sized resistors, then you should probably use a larger capacitor to compensate.

However, using a smaller capacitor with larger resistors gives a very large advantage in the amount of wasted current. If you are using smaller resistors, then Ohm's law indicates that we will have larger currents for a given voltage. Since $V = I \cdot R$, if you lower the R you will increase the I. So, having a higher resistance means that your RC circuit will use much less current.

Remember that we aren't actually *using* the current to *do* anything except keep time. The current in our RC circuit is not used to power the LED (the 555 does that through the power source), it isn't used for anything else, it is just used to keep time. Therefore, pretty much all current used by the RC circuits is wasted. We have to use it, but any smaller currents we can get away with, we should!

This gets even more pronounced when the capacitor is discharging. When Pin 7 ($DISCHARGE$) switches to ground, not only does it discharge the capacitor, but it also creates a useless waste of current going from the voltage source through R1. In our oscillator configuration, you can't get rid of this, but having larger resistors will reduce the amount waste.

So, in short, if you have higher-valued resistors to compensate, your circuit will waste much less current by using smaller capacitors.

Review

In this chapter, we learned:

1. Because this material is based so heavily on RC circuits, you may want to review the material in Chapter 18.
2. When something oscillates it moves back and forth between a set of values.
3. In electronics, oscillators usually refer to circuits whose output voltages go back and forth between two different values.
4. Oscillations are usually described by their period or frequency.
5. The period of an oscillation is the time that it takes to go through one entire cycle (usually in seconds).
6. The frequency of an oscillation is the number of times that an oscillation occurs per second, which is simply the reciprocal of the period (i.e., $\frac{1}{\text{period}}$), with a unit of hertz (cycles per second).
7. Oscillating circuits are used in a number of circuit applications, including sound production, time keeping, coordinating activities, radio transmissions, and motor control.
8. Oscillating circuits are often built with RC time circuits which control the time periods of the oscillations.
9. The NE555 (often referred to as a 555 timer or just the 555) is an integrated circuit which allows for several timing applications including making oscillating circuits.
10. The NE555, when setup as an oscillator, is controlled by two resistors and a capacitor.
11. The NE555 can be setup to monitor the charge of the capacitor. It has two pins for monitoring the voltage, $\overline{Trigger}$ (which checks for the capacitor to drop below $\frac{1}{3}$ supply voltage, and $Threshold$ (which checks to see when the capacitor is charged above $\frac{2}{3}$ of supply voltage.
12. The NE555 cycles between charging and discharging the capacitor from $\frac{1}{3}$ of supply voltage to $\frac{2}{3}$ of supply voltage and back (using $\overline{Trigger}$ and $Threshold$ to check the voltage level).
13. The $Discharge$ pin of the NE555 acts like it is disconnected when the capacitor is charging, and is connected to ground to allow for a path for the capacitor to discharge.
14. The $Output$ pin of the NE555 is turned on (higher voltage level) while the capacitor is charging, and off (low voltage level) when the capacitor is discharging. The NE555 output operates at about 1.7 V less than the source voltage when on, and can source a maximum of 200 mA to the output circuit.
15. The $\overline{Reset}$ pin can be given a low voltage to reset the whole device. If it is unused, it should just be tied to a positive voltage line.
16. The $Control$ pin is attached to a capacitor in order to regulate and stabilize the circuit operation.
17. The RC circuit takes 0.693 time constants to charge from $\frac{1}{3}$ voltage to $\frac{2}{3}$ voltage or to discharge the other way. Therefore, once you have the RC time constant, multiply by 0.693 to find the actual time it will take.

18. The RC circuit utilizes *both* resistors when charging, but only *one* resistor when discharging. This means that charging and discharging each have their own RC time constants.
19. Because the charge circuit uses two resistors while the discharge circuit only uses one, the charging portion of the oscillation period will always be at least a little longer than the discharging portion.
20. The period of the oscillation is the combination of both the charge time and the discharge time.
21. When calculating resistors for an RC time circuit, it is best to calculate the discharge resistance first, since it only uses one resistor (R2). Then you can calculate the combined resistance for the charge circuit, which allows you to deduce what the R1 resistor should be.
22. When choosing components for a given RC time constant, you can choose a variety of combinations of capacitor/resistor values for the same result. Choosing a smaller capacitor and a larger resistor will save power in the circuit.
23. An equation for determining the frequency of a 555 oscillator circuit can be found in Appendix E.3.

Apply What You Have Learned

1. Take a look at the circuit in Figure 19.2 (this will be used as the basis for the problems in this section). Copy this circuit to a piece of paper. Draw a line in one color showing how the current flows in the main circuit as it charges the capacitor. With a different color, draw a line showing how current flows as the capacitor discharges. Use arrows to indicate current direction.
2. Why is R1 important? What would happen if we just replaced it with a wire?
3. Why are there two different pins on the NE555 connected to the capacitor? What type of circuit (that we have discussed in this book) do you think they are connected to inside the chip?
4. Why is the charging time of the NE555 always at least a little longer than the discharging time?
5. Why does the NE555 stay in the on state a little longer when it first turns on?
6. Let's say that we wanted our circuit to be on for 2 seconds and off for 1 seconds. Keeping the same capacitor, what values should we use for R1 and R2 to accomplish that?
7. Let's say that we wanted our circuit to be on for 10 seconds and off for 3 seconds. Keeping the same capacitor, what values should we use for R1 and R2 to accomplish that?
8. The factory called and said that they were out of the capacitor we wanted for the circuit, and instead only had a 23 µF capacitor that we could use. Recalculate the previous problem using this new capacitor value.
9. How much current is our output sourcing from the chip?
10. When the chip first turns on (and thus the capacitor is empty and at 0 V) how much current is the RC circuit using?

Chapter 20

An Introduction to Sound Production

In Chapter 19, we learned to make an oscillator circuit. Oscillations affect a lot of areas of electronics, but the one that is most directly usable (well, besides making blinky lights) is in making sounds.

20.1 How Sound is Produced by Speakers

As we mentioned in Chapter 19, sound is the result of vibrations (i.e., oscillating motions) in the air. These vibrations are produced in electronics with a speaker when the speaker oscillates back and forth. The speaker oscillates back and forth because it is connected to a magnet and a coil. When the electricity in the coil oscillates between more positive and more negative charges, the magnet is attracted and repelled from the coil, moving the speaker back and forth.

The frequency of this oscillation will determine the pitch of the sound (i.e., how high or low the sound is). If the frequency is higher (shorter periods), then the pitch is higher. If the frequency is lower (longer periods), then the pitch is lower.

Now, compared to the blinking lights we worked with in Chapter 19, sounds that you can hear are all of a much higher frequency. The bottom end of the hearable audio is about 20 Hz—that is, 20 cycles per second. The top end is about 20 kHz (i.e., 20,000 Hz). These values vary by individual, but this is a pretty good guide for most people. If we tried to blink an LED that fast, we just would not be able to see it—it would just look like a dimmer-than-normal light.

20.2 Graphing Electricity

Now, when we deal with circuits that are oscillating quickly, we need to have a way to visualize what is happening. With circuits that have one or two states, we don't need to visualize much—we just need to

Figure 20.1: A Graph of the Capacitor Voltage in a 555 Oscillator

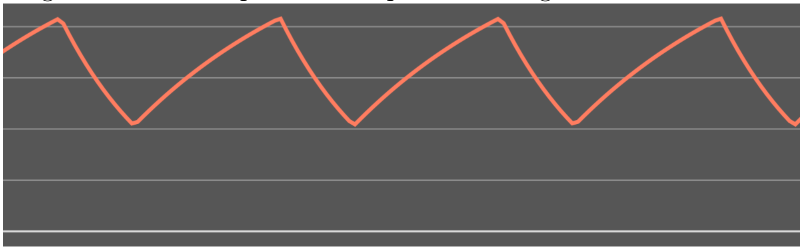
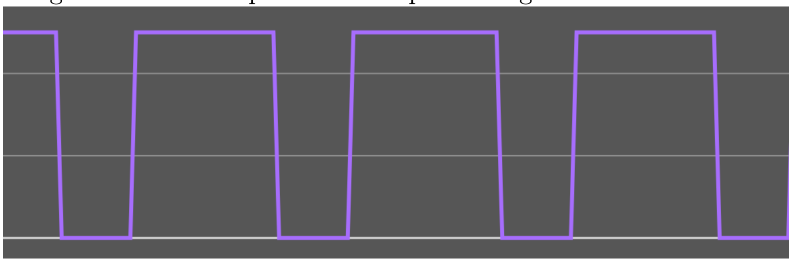


Figure 20.2: A Graph of the Output Voltage in a 555 Oscillator



calculate what the values are. However, with circuits that are continually oscillating (such as sound circuits), it is helpful to be able to graph what the voltages are at different points in time.

There are several ways to graph electricity. One of the most common ways is to plot *time* on the x-axis and *voltage* on the y-axis. This gives a visible representation of how the voltage is varying within the circuit. Now, because each point in a circuit has a different voltage, you have to specify *which point* on the circuit you are graphing. For instance, if you take the 555 oscillator circuit from Chapter 19 (i.e., Figure 19.2), the two places which you might want to graph the voltages are either (a) right before the capacitor, or (b) right after the output pin.

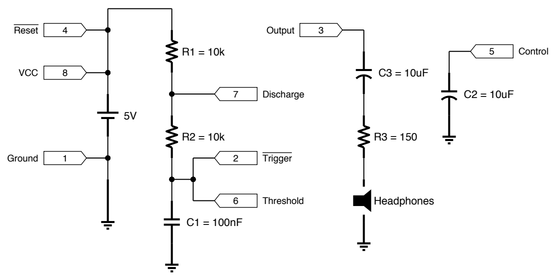
These will give *very* different graphs, but both of them are instructive. The graph of (a) will show you what the input side of the circuit looks like, and the graph of (b) will show you what the output side of the circuit looks like.

Notice that Figure 20.1 changes fairly smoothly (except when it changes directions). This is because capacitor charging causes the voltage to change smoothly over time. It charges up until it reaches $\frac{2}{3}$ supply voltage and then discharges down to $\frac{1}{3}$ supply voltage. It does this over and over again as you can see on the graph.

The output, however, is either *on* or *off*. Therefore, Figure 20.2 shows a very jagged graph. This is known as a **square wave**, because it is basically rectangular. The voltage just goes from zero to the target voltage almost instantly and then after it stays there a bit the voltage goes back down again just as instantaneously as it rose.

In addition to graphing voltage, we can also graph current in the same way, though it is harder to measure. Because voltage can be measured with simple probes and measuring current requires replacing a wire, most of the time people just focus on voltage measurements.

Figure 20.3: Schematic for a Simple 555-based Tone Generator



Special devices known as **oscilloscopes** can be used to measure voltage changes over time. Figures 20.1 and 20.2 were made by hooking up an oscilloscope to the circuit while it was in operation. Oscilloscopes used to cost thousands of dollars, but now you can pick up a small handheld oscilloscope for under $50.

Usage of an oscilloscope is outside the scope of this book, but the basics are simple enough. An oscilloscope usually has an active probe and a ground probe. You hook up the ground probe to the ground on your circuit, and you hook up the active probe to the point in the circuit that you want to measure. Then, you look at the screen, and it will graph for you what the past and current voltage is at that point. Most oscilloscopes have all sorts of adjustments, such as how wide of a voltage range you want to measure, and how long of a time window you want to show on the screen. In any case oscilloscopes provide graphical views of oscillating voltages.

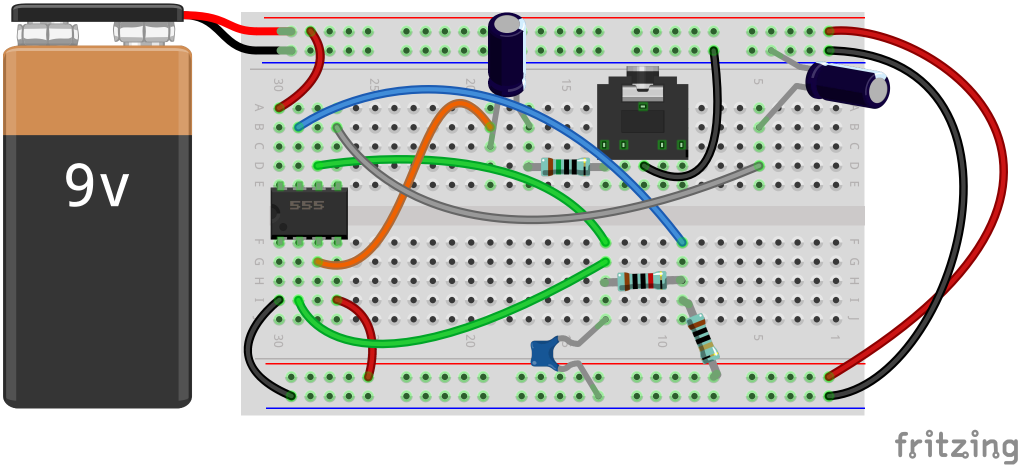
20.3 Outputting a Tone to Headphones

In this section, we are going to modify the circuit in Figure 19.2 to add in a headphone output. Figure 20.3 shows the final circuit, and Figure 20.4 shows how to build it. This circuit has several changes to our original circuit that we will discuss in this section.

The first changes to this circuit are to the RC time circuit. Because we want the circuit to be in audio range, we are making a much higher frequency (i.e., a shorter period). To do this, we swapped out the electrolytic capacitor for a ceramic disk capacitor of 100 nF. Then, we dropped the resistors down to 10 kΩ each. This will make a tone with a period of 0.003 seconds. Taking the reciprocal gives us a frequency of about 333 Hz. This is well within hearing range for most people. You can adjust the resistors and capacitors how you wish for different tone frequencies. We are merely using the equations from Chapter 19 to determine the period and frequency.

The strange change is in the output circuit. When we were blinking the LED, we just used a medium-sized resistor to limit output current. Here, however, we are using a combination of a capacitor and a resistor. This *looks like* an RC time circuit—and it would be, if it had a constant voltage going to it. However, in this circuit, the voltage going to the RC circuit is fluctuating, and that introduces a whole host of new considerations.

Figure 20.4: Breadboard Layout for 555-based Tone Generator



20.4 AC vs. DC Current

In Chapter 4 we introduced the ideas of *direct current* (DC) and *alternating current* (AC). In DC circuits, the circuit has a more-or-less constant voltage. Our power supply is at a certain voltage, our output is at a certain voltage, etc. In AC circuits, however, the voltage oscillates back-and-forth. These oscillations introduce a whole new set of considerations.

In pure AC circuits, voltage and current actually swing both to positive and negative values. What is a negative current? A negative current happens when the electricity flows in the *opposite* direction. Thus, in a *pure* AC circuit, electricity flows back-and-forth, switching off between which direction it is running, spending about even time in each direction.

Some components, such as speakers, assume that they are going to receive or process pure AC currents. That is, they *expect* the current to switch direction at some point. As mentioned earlier, the speaker is driven by changing voltages in a coil, which alters the attraction of the coil to a magnet. These variations in attraction and repulsion moves the coil back and forth, which moves the speaker cone, which vibrates the air, which vibrates your eardrum, which you hear. Speakers expect the oscillating current to go back and forth each direction about evenly.

However, in our circuit, the voltage only swings between a positive voltage and 0 V. If you look at the graph in Figure 20.2, notice that while the voltage goes up to a positive voltage, the *lowest* that it ever goes is zero. Therefore, it is not a pure AC circuit, because it is not centered around 0 V. Instead, the AC has a **DC bias voltage**. That is, the output voltage can be thought of as a combination of an AC voltage signal added to a DC voltage.

20.5 Using Capacitors to Separate AC and DC Components

Sometimes having a DC bias is good, and sometimes we need to separate out our AC and DC signals. Capacitors are excellent at this. Capacitors are said to *allow* AC currents to flow and to *block* DC currents. This is a simplistic view, and we will get a little more nuanced in future chapters, but it works for now.

To understand why this happens, let's remember what a capacitor does physically. It stores charge—like a small battery. Remember, even though the pathway between the plates of a capacitor is blocked, when a positive charge accumulates on one side, it pulls electrons into the other side, which means that the other side gets more positive as well. Do you remember what happens when the capacitor *first* starts charging? The capacitor basically acts as a short circuit. As the capacitor fills up, it starts acting more and more like a resistor, preventing current from flowing.

Thus, when given a constant voltage, once the capacitor is nearly full, it essentially stops getting more charge (or comes very close to it). Therefore, once it is full, it is basically *blocking* any more current from flowing. Since what goes onto one side of the capacitor affects what is on the other side, this same blockage will block the *transmission* of the current to the other side as well. Thus, in the long run, if you have a DC voltage, the capacitor will eventually block current flow. Thus, the current on the *other* side of the capacitor will be *zero*.

However, now consider what happens if the voltage *changes*. If the voltage changes, then the capacitor will allow current to flow through. If the voltage goes up, then the capacitor has more storage available (since the amount of storage depends on voltage). While it is charging to the new level, current will be flowing. If the voltage goes down, then the capacitor will actually have to discharge back into the circuit.

Now, if the capacitor discharges back into the circuit, *which way is the current flowing*? Well, that means the current from the capacitor is now flowing in the *opposite* direction!

Thus, what ends up happening, is that the capacitor winds up only sending *changes* in voltage and current to the other side of the circuit! While the capacitor is charging and discharging, charge is moving through both sides of the capacitor. Thus, when the voltage (and therefore the charge) on the capacitor is changing, current is indeed flowing. Now, when the voltage stays the same, no electrons move, no matter what the voltage is. Therefore, even though you have a positive voltage on one side, if the voltage is not changing, no current is flowing. Therefore, on an unchanging current, the voltage on the other side of the capacitor will be zero.

Since the changes go up and down, but the DC bias voltage does not go up and down, this has the effect of sending AC current through the capacitor, but blocking the DC bias voltage.

Therefore, capacitors are often used in series in a circuit to couple together parts of circuits that are pure AC with other parts of the circuit that have a DC bias. Since the output of the 555 is DC biased, and speakers generally are optimized for pure AC output, the capacitor in our output circuit filters out the DC bias and gives a pure AC signal.

A capacitor used in this way is known as a **coupling capacitor**.

Alternatively, if for some reason you wanted *only* the DC component, you could wire the capacitor to go to ground. This sends the AC part of the signal to ground, leaving only the DC component in the circuit. In such a scenario, the capacitor is being used as a **filter capacitor**.

Now, using a coupling capacitor does add in a small amount of distortion, both because DC bias voltage does have some effect on the signal, and because different capacitor values are optimal for coupling different frequencies. For audio applications, a capacitor somewhere between 10 nF and 10 µF should be used.

20.6 Speaker Wattage

Next in the circuit is the R3 resistor. The R3 resistor is there to limit the output signal to the headphones. Headphones and speakers are all a little strange—there is very little standardization. Different headphones have different resistances in the speakers, and different tolerances for how much wattage can be put through them. Speakers are usually rated by both (a) how much resistance they normally add to the circuit, (b) how loud they are at a given wattage of power, and (c) what their maximum wattage is. Even though there is quite a bit of variance, for headphones, you can be fairly safe by estimating that the headphones will act as 16 Ω resistors, and that they can consume a maximum of 20 mW.

The output of the 555 timer is 1.7 V less than my supply voltage. So, for a 5 V source, the output will be 3.2 V. However, since we have now centered it on 0 V, the output will actually only be half of that—1.6 V. We can use the formula $P = \frac{V^2}{R}$ from Chapter 11 to determine how many watts this will supply. If the speaker is 16 Ω, then the power used by the headphone without the extra resistor will be $\frac{1.6^2}{16} = 0.16\,\mathrm{W} = 160\,\mathrm{mW}$. Therefore, the R3 resistor pulls out some of that power.

With the resistor, the combined power usage of the resistor and the headphone speaker is 166 Ω. Therefore, the power here is $\frac{1.6^2}{166} = 0.015\,\mathrm{W} = 15\,\mathrm{mW}$. Remember, though, that this is the *combined* power of both the resistor and our speaker. The speaker is only supplying about $\frac{1}{10}$ of the resistance, so it is only using up $\frac{1}{10}$ of the power, or 1.5 mW.

Now, the calculation for this is relatively easy because we are working with square waves. The calculation becomes harder for different types of output, because you have to take into account the *shape* of the wave. However, we won't go into that in this book. This calculation using the peak voltage provides a simple method which will give you a good starting point, and you can judge for yourself if you need more or less resistance for your own circuits.

20.7 Sound Control

Now, as I mentioned, all headphones are different, and, with the exception of *having* a coupling capacitor, they all have different ranges and need different amounts of power. Usually this is accommodated by having a volume control.

There are two basic ways to do a volume control. The first is with a **variable resistor**. On a variable resistor, you usually turn a knob and the resistance changes. Variable resistors go by different names—variable resistor, adjustable resistor, rheostat, and trimming resistors. Trimming resistors are the easiest to use for this, but probably the hardest to find. To use a variable resistor, you would need to find one with the right range of values, and then simply replace the output resistor R3 with your variable resistor.

A more common type of component is a potentiometer. A potentiometer is basically a variable voltage divider. It has three leads—input, ground, and output. When you turn the knob, it adjusts the relative resistance of each side of the voltage divider to vary what is coming out of the output.

You can use a potentiometer for a volume control—take the output from the coupling capacitor to the positive input of the potentiometer, run the ground of the potentiometer to the ground rail, and put the output to the speaker. You can also, however, just use half of the potentiometer as a variable resistor. Most potentiometers are made using what is essentially two variable resistors. By using the positive pin and the output pin alone (leaving the ground pin unconnected), the potentiometer becomes a simple variable resistor. Potentiometers vary widely in how much resistance they offer, so if we were to add one as a volume control we would need to make sure its resistance range approximately matches what is needed (around $150\,\Omega$).

Review

In this chapter, we learned:

1. Sound is the result of oscillations in the air that is picked up by your eardrums.
2. Sound can be generated by an oscillating speaker cone vibrating against the air.
3. The oscillations in a speaker cone are made by a magnet being drawn and repelled to another magnet by oscillations in electrical power.
4. Sound generally has higher frequencies (i.e., shorter periods) than what we use for flashing lights.
5. Hearable sound frequencies range from 20 Hz to 20 kHz.
6. On circuits where voltage and/or current change with time, it is often helpful to plot their changes at specific points on a graph to help visualize what is happening.
7. The output of the 555 timer is known as a square wave because it has steep changes in voltage at specific points, making a rectangular-shaped graph.
8. An oscilloscope can be used to measure and record these types of graphs.
9. Voltages that oscillate quickly with time are known as alternating current, or AC voltages.
10. Oscillating voltages that do not spend roughly equal amounts of time on either side of zero volts are said to have a DC bias voltage.
11. The DC bias voltage is how much voltage you would have to subtract from the voltage in order for the voltage to be centered on zero volts.
12. Most circuits have DC bias voltages, but most output devices (such as speakers) need the DC bias voltage removed and only use the AC component of the signal.
13. DC bias voltage can be removed by placing a coupling capacitor in series with the output signal. The capacitor will only transmit voltage *changes*, thus removing the DC bias voltage.
14. Speakers and headphones vary considerably in their properties.
15. The most important considerations are how many ohms of resistance they have and how many watts are needed to drive the sound.
16. For headphones, a good starting assumption is that the speaker is 16 Ω and needs under 20 mW of output.
17. If your output signal is larger than this, be sure to add a resistor in series to consume some of the output signal's power.
18. The output resistor can be replaced with a variable resistor or a potentiometer to have a user-controlled output setting, also known as a volume control.
19. A potentiometer is a variable voltage divider. However, by using only the positive and output terminals, it can be used as a variable resistor instead.

Apply What You Have Learned

1. Why is the input voltage signal to the 555 timer smooth, but the output is square?
2. Will increasing the resistance of R1 and R2 make the pitch higher or lower?
3. Can you think of a way to modify the circuit so that the pitch of the sound can be adjusted while the circuit is on?
4. Given the circuit in Figure 20.3, what power would be delivered to your headphones if you were using an $8\,\Omega$ speaker instead of the $16\,\Omega$ speaker? What about a $100\,\Omega$ speaker?
5. The frequency of the A note above middle-C on the piano is 440 Hz. Design a modification to this circuit that will yield this frequency.
6. The output of the 555 is 1.7 V less than the power supply used. What is the effect on the wattage to the headphones if we change the power supply to be a 9 V power supply?

Chapter 21

Inductors

In this chapter, we will begin our study of **inductors** and **coils**.

21.1 Inductors, Coils, and Magnetic Flux

In Chapter 17, we learned that capacitors stored charge by using an electric field. We also learned that capacitors continued to hold their charge even after it was disconnected from the rest of the circuit. We learned in Chapter 20 that capacitors blocked DC signals but allowed AC signals to pass through.

21.1.1 What is an Inductor?

An inductor is kind of like the capacitor's evil twin. It behaves in some ways that remind us a lot of capacitors, but it is operating on a different aspect of electrical behavior. Capacitors store charge and release it in response to voltage changes. Inductors, instead, store **magnetic flux** and release it in response to current changes. Thus, capacitors tend to even out voltages, and inductors tend to even out currents.

Figure 21.1 shows what an inductor looks like in a schematic. Inductors are non-polarized, so they can be wired in either direction. The symbol loosely represents a coil of wire, because that is what inductors are essentially made of.

Figure 21.1: The Symbol for an Inductor

21.1.2 What is magnetic flux?

When current moves in a wire, it creates a very tiny magnetic field. It's not large enough to pick up anything, but it is present. Flux is the total amount of magnetism present in an inductor. Since this is an engineering book, not a physics book, we won't spend a lot of time trying to come to grips with what flux is and how it works. We will simply understand that it is the total size of the magnetic field of a component, and it is measured in Webers (Wb). To get a feel for what a Weber is like, a small bar magnet has a flux of around $\frac{1}{1000}$ Wb.

As a side note, when we say that something is magnetic, we are usually not talking about the total flux of something, but of the *density* of that flux—the amount of flux in an given area. Flux density is measured in Teslas (one Tesla is $\frac{1\,\text{Wb}}{1\text{ meter}^2}$), but we will not concern ourselves with Teslas or flux densities for this course.

21.1.3 What is the difference between electric vs. magnetic fields

Now, when we talked about capacitors, we talked a little bit about electric fields. Electric fields and magnetic fields are related, but different. An electric field is generated by a difference in charge between two surfaces. Electric fields can exist even when no current is moving at all—there just has to be two differently-charged surfaces. Basically, any charged object will induce a force on another charged object for a certain distance, and this is the electric field.

The magnetic field, however, only exists when a charge is moving. When a charge is in motion, in addition to the electric field, it also creates a *magnetic* field surrounding itself, going perpendicular to the wire. This field also exhibits a force on charged objects within a small distance, but a much larger distance than the electric field. Additionally, when the current in the wire slows down, the magnetic field will convert its own energy into current in the wire.

The size of a magnetic field within a single wire is very, very small, and can be ignored. However, the strength of the magnetic field of a wire can be increased by wrapping (coiling) it around a cylindrical core. This aligns the magnetic fields of the wires so that the fields can each be added together to produce a combined magnetic field. Each turn around the core adds an additional bit to the magnetic field. Devices based on this priciple are called coils or an **inductors**.

When an inductor is first turned on, most of the current goes into creating the inductor's magnetic field. Then, as the magnetic field is setting up, it allows more and more current to flow, until it hits a steady state. Then, if the current flow reduces, the energy from the magnetic field gets transformed into current and goes out to try to make up the difference.

While a capacitor stores energy as a charge and releases it when there is a voltage change, an inductor stores energy as magnetic flux and releases it when there is a current change. An inductor's inductance is measured using the **Henry** (H). The core equations of capacitors and inductors are related as well. The defining equation of a capacitor is $Q = C \cdot V$, where Q is the charge in the capacitor. The defining equation of an inductor is just as simple:

$$\phi = L \cdot I \tag{21.1}$$

In this equation, ϕ is the magnetic flux in the inductor (in Webers), L is the inductance (in Henries), and I is the current (in Amperes). The **Henry** is the primary unit of inductance, and has an abbreviation of H.

Example 21.19 If I have a 50 microhenry inductor and have a constant current of 2 milliamps, how much magnetic flux is being stored?

$$\phi = L \cdot I$$
$$L = 50\,\mu\mathrm{H} = 0.00005\,\mathrm{H}$$
$$I = 2\,\mathrm{mA} = 0.002\,\mathrm{A}\phi \qquad = 0.00005 \cdot 0.002$$
$$= 0.0000001\,\mathrm{Wb} = 0.1\,\mu\mathrm{Wb}$$

Therefore, we have 0.0000001 Webers of flux, or 0.1 microwebers of flux.

Therefore, when a relatively constant amount of current flows, it is easy to calculate the amount of flux in the magnetic field.

21.2 Induced Voltages

Changes in the flux of a magnetic field induces voltages. The amount of voltage induced depends on how fast the flux changes. The induced voltage is essentially the change in the flux divided by the number of seconds that it took for the change to occur. If the flux decreases, the energy is converted into voltage, which goes up. If the flux increases, the energy was taken from the voltage, which goes down. So, if there was a decrease of 10 Wb over the course of 2 seconds then the amount of voltage induced would be $\frac{10\,\mathrm{Wb}}{2\text{ seconds}} = 5\,\mathrm{V}$.

The formal statement of this is known as Lenz's law. It is given as follows:

$$V_{average} = -\frac{\text{change in }\phi}{\text{change in time}} \tag{21.2}$$

The average voltage produced by the change in a magnetic field over a given time period is the same as the amount of flux that was reduced by the field divided by the same time period.

Now, the amount of flux in the inductor will change with the current, as indicated by Equation 21.1. When the current decreases, it will cause the flux to be converted into voltage. When the current increases, it will add more flux into the magnetic field, using up voltage.

When the amount of flux changes, it creates a voltage. The amount of flux change (in Webers) divided by the amount of time it took to change (in seconds) will yield the voltage produced by the change. Therefore, when the current drops, the flux will be converted to voltage. If we add in voltage, it will also increase the current.

21.3 Resisting Changes in Current

Ultimately, what an inductor is doing is resisting changes in current. When the current goes up, the current is first used to construct the magnetic field, and therefore it takes some time to allow the full amount of current through. When the current goes down, the flux of the magnetic field decreases, which gets converted back to voltage, which induces more current.

The inductor, with regards to current, is the opposite of the capacitor. With direct current, the capacitor, when first connected to the circuit, acts as a short circuit—the current basically flows right through until the capacitor starts to fill up. When the capacitor is full, then it acts like an open circuit—blocking any more current from flowing.

The inductor is the opposite. When first connected to the circuit, the inductor acts like an open circuit—the current is basically being used to construct the magnetic field. As the magnetic field strength increases, more and more current is allowed to flow. Once the magnetic field flux matches what it should be for the given current, the current flows freely, as if the inductor were not even there, like a short circuit.

In summary, we can say that a capacitor acts as an open circuit for sustained DC current and as a short circuit for alternating current. The inductor acts as a short circuit for sustained DC current and as an open circuit for alternating current.

21.4 Analogy from Mechanics

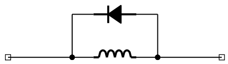
If you are into mechanics, you can think of an inductor as a flywheel. Flywheels store mechanical energy into the motion of a large or heavy wheel. It takes energy to get the wheel spinning, but once it is spinning, the wheel itself can continue to drive the mechanism. The wheel is used to even out the drive of the other components of the mechanism.

For instance, an engine driven by pistons will have somewhat irregular motion, because the force of the pistons is not constant through their motion. However, attaching a flywheel will even out the energy output. When the pistons are delivering more power, most of the excess will be going to the flywheel, and when the pistons are delivering less power, the mechanism can be driven by the force of the flywheel.

21.5 Uses of Inductors

Inductors are used in a very wide variety of applications—much more so than capacitors. Capacitors are used primarily for their effects *within* electronic circuits—filtering noise, blocking DC current, coupling DC-biased circuits, etc. However, the electric field created on the plates of the capacitor is fairly useless on its own because the field fades so quickly with distance. Inductors are used for similar things as capacitors within circuits (their operation being largely the counterpart of what a capacitor would do), but additionally, the magnetic field of the inductor has innumerable uses because its effects are stronger further away. These uses include:

Figure 21.2: A Snubber Diode



- Inductors are used to make **electromagnets**, for picking up and setting down large objects.
- Inductors are used to make **transformers**, which use the magnetic field in one inductor to generate a current in another inductor.
- Inductors are used to make motors, where the electromagnetic coils are used to turn a shaft.
- Inductors are used to make speakers, which use the magnetic field to move the speaker diaphragm back and forth.
- Inductors are used to make relays, which use the magnetic field to open and close switches.

These are just some of the uses of inductors. In short, the magnetic field created by the inductor is what allows many of the interfaces between electronic devices and the real world.

21.6 Inductive Kick

One important thing to keep in mind when using inductors is the concept of inductive kick. Lenz's law (Equation 21.2) shows that decreases in the magnetic flux will induce a voltage. Since the magnetic flux is divided by time to get the voltage, that means that a shorter timespan will generate a larger voltage. Thus, a sudden decrease in magnetic flux will cause a voltage spike.

But what controls the flux? If you go back to Equation 21.1, we can see that a decrease in current will decrease the magnetic flux. Therefore, a sudden decrease in current will cause a sudden decrease in the magnetic flux which will then cause a large voltage spike within the inductor itself. This spike is known as an **inductive kick** and can damage nearby electronic components. To avoid an inductive kick, a **flyback diode**, also called a **protection diode** or a **snubber diode**, can be used.

A flyback diode is a regular diode (*not* a Zener diode) wired backwards across the terminals of an inductor. Under normal operation the diode won't conduct. However, when the diode is shut off, it provides a safe path for the generated voltage to pass through (back through the other side of the inductor), and allows the inductor to bleed off voltage in a much more controlled manner.

Figure 21.2 shows how this is wired up. As you can see, under normal operation, the current flows in the direction of the arrow. Since the left-hand side is more positive than the right-hand side, no current can flow through the diode. However, when the current is shut off, the right-hand side becomes more positive very quickly, and the diode feeds the excess current back through the inductor to allow the extra energy dissipate more slowly.

You might be wondering why the voltage doesn't just shift back to the left side on its own once the right-hand side is more positive. The answer is that the magnetic field that is generating the voltage is itself directionalized within the inductor. The field's movement is such that it is essentially pushing current to the right (which is why a voltage is being produced). Therefore, the flyback diode carries this excess voltage back to the left-hand side of the diode.

Flyback diodes are used with all sorts of inductors (motors, electromagnets, etc.) anywhere where there are components that could be damaged by an inductive kick. For basic applications, nearly any type of diode will work for a flyback diode. However, diodes differ in their speed in reacting to voltage changes. In some circuits, the speed that a diode reacts to changes in voltage can be important.

Review

In this chapter, we learned:

1. Inductors are electronic components that are made of winding wire around a core which allows them to store charge in their magnetic fields.
2. The strength of a magnetic field is the magnetic flux and is measured in Webers (Wb).
3. While an *electric* field is made from the *presence* of charges, the *magnetic* field is made from the *movement* of charges (i.e., the current).
4. When the current going into an inductor increases, the extra current is first used to build up the flux of the magnetic field before achieving a new steady state.
5. When the current going into an inductor decreases, the flux of the magnetic field is converted into a voltage, which increases the output current, resisting the change in current.
6. Inductors oppose changes in current. They act as resistors to AC current and as short circuits to DC current.
7. An inductor can be thought of similar to a flywheel in mechanics, which stores energy in a rotating wheel.
8. Inductors are useful because not only do they have interesting electric properties, their magnetic field also allows them to interface into the real world because magnetic field effects have a much longer reach than electric field effects.
9. When current to an inductor is suddenly shut off, it creates a large voltage, known as an inductive kick.
10. A snubber diode is used to mitigate against the negative effects of an inductive kick.

Apply What You Have Learned

1. If I want a circuit to block DC current but allow AC current, should I use an inductor or a capacitor?
2. If I want a circuit to allow DC current but block AC current, should I use an inductor or a capacitor?
3. Why are inductors used so much in systems that interact with the outside world?
4. Why does inductive kick happen?
5. Draw a schematic of an inductor where the positive side of the inductor has a switch and the negative side is connected to an LED and a resistor. Add in a snubber diode to protect the LED from the effect of turning off the switch.
6. If I have an inductor that is 5 H and has a steady current going through it of 2 A, what is the size of the magnetic flux in the inductor's magnetic field?

7. If I have an inductor that is $7\,\mu\mathrm{H}$ and has a steady current going through it of $3\,\mathrm{mA}$, what is the size of the magnetic flux in the inductor's magnetic field?
8. If I have a $4\,\mathrm{H}$ inductor with $0.3\,\mathrm{Wb}$ of flux in its magnetic field, how much current is flowing through it?
9. If an inductor's magnetic field has $5\,\mathrm{Wb}$ of flux and it decreases to $3\,\mathrm{Wb}$ of flux over 2 seconds, what is the average voltage produced over that timeframe?
10. If an inductor's magnetic field has $1\,\mu\mathrm{Wb}$ of flux and it increates to $2\,\mu\mathrm{Wb}$ of flux over 0.4 seconds, what is the average voltage produced over that timeframe?
11. If the current flowing through a $3\,\mathrm{H}$ inductor drops from $7\,\mathrm{mA}$ to $1\,\mathrm{mA}$ over a period of 0.01 seconds, what is the average voltage produced over that time period?

Chapter 22

Inductors and Capacitors in Circuits

In this chapter we will look at a few of the basic uses of simple inductors.

22.1 RL Circuits and Time Constants

Just like we had an RC circuit for capacitors, there is a similar circuit for inductors—the RL circuit. Just like inductors are alter ego of the capacitor, the RL circuits are the alter ego of RC circuits.

An RL circuit is a circuit consisting of a resistor (R) and an inductor (L) in series with each other. They are similar in construction and usage to the RC circuits we looked at in Chapter 18, but have some important differences.

In RC circuits, the RC time constant was the amount of time it took to charge a capacitor to 63.2% of full voltage when coupled through a resistor. That is, after one time constant has passed, the voltage between the legs of the capacitor will be 63.2% of supply voltage.

In RL circuits, the RL time constant is the amount of time it takes to charge the inductor's magnetic field 63.2% of its final value. Since the size of the magnetic field and the current are directly related to each other, this is also the amount of time it takes to get the current up to 63.2% of its final rate.

The way that the RL time constant is calculate *is different from* the way that RC time constants are calculated. The RL time constant is found by *dividing* the inductance in henries (L) by the resistance in ohms (R).

$$\tau = \frac{L}{R} \tag{22.1}$$

Figure 22.1 shows the relationship between the number of time constants, the current through the inductor,

Figure 22.1: RL Time Constants

# of Time Constants	**% of Current**	**% of Voltage**
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%

and the voltage across the inductor. This is the same table as the one for RC time constants (Figure 18.1) except that current and voltage are swapped with each other.

Example 22.20 Let's say that we have a 2 H inductor in series with a 500 Ω resistor connected to a 5 V source. How long will it take before the inductor has 2.5 V across its terminals?

To solve this, recognize that 2.5 V is basically half of the voltage source. Therefore, we need to look at Figure 22.1 and find the one which is closest to having 50% of the voltage. That is 0.7 time constants.

Now, we need to figure out what the time constant for this circuit is. The inductance is 2 H and the resistance is 500 Ω. Therefore, according to Equation 22.1, we divide the inductance by the resistance:

$$\begin{aligned}\tau &= \frac{2}{500} \\ &= 0.004 \text{ seconds}\end{aligned}$$

Therefore the time constant is 0.004 seconds. We are wanting 0.7 time constants, so the final answer is $0.004 \cdot 0.7 = 0.0028$ seconds.

22.2 Inductors and Capacitors as Filters

As we have mentioned, a general way of thinking about capacitors and inductors is that capacitors allow AC current but block DC current. Inductors are the other way around. Inductors allow DC current but block AC current.

This can also be thought of in terms of frequency response. When dealing with signals (audio circuits, radio circuits, etc.) you often times want to deal with certain frequencies and not others. With an inductor, the

Figure 22.2: Removing High Frequencies Using an Inductor

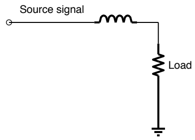
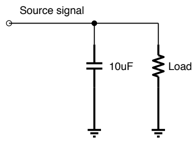


Figure 22.3: Removing High Frequencies Using a Capacitor



lower the frequency is, the easier it is to pass through from one side to the other. With a capacitor, the higher the frequency is, the easier it is to pass through from one side to the other.

Many audio systems have different speakers optimized for different frequencies. A common setup is to have two speakers—a woofer which handles the low pitches and a tweeter which handles the higher pitches. By using capacitors and inductors, circuit designers can customize which frequencies go to which speakers.

Radio systems also utilize capacitors and inductors. Each radio station operates on a specific carrier frequency. A **carrier frequency** is the dominant frequency used to carry a signal. When building a radio receiver, capacitors and inductors are used to isolate the specific frequency from all of the frequencies being transmitted over the air.

Chapter 23 will discuss the mathematics behind this further.

22.3 Parallel and Series Capacitors and Inductors

Capacitors and inductors can each often take on the role of the other in frequency filtering. As we have mentioned, you can use a capacitor to allow AC signals and block DC and low frequency signals. Inductors do the opposite—they allow DC and low frequency signals and block AC signals. However, in a pinch, you can actually get each one to do the job of the other.

Imagine that you want to get rid of noise in a circuit. Noise is essentially high-frequency AC current. Using the previously defined rules, we might want to put an inductor in series with the circuit to remove noise. Figure 22.2 shows what this looks like. There is, however, another option.

Instead of putting an inductor in series with the circuit, we can instead wire a capacitor that goes to ground in parallel with the circuit. Figure 22.3 shows this configuration. The way to think about this is that, since AC signals travel through a capacitor, the capacitor is shunting off AC currents to ground before they get to the load.

Likewise, the same can be done for low-frequency filtering. Normally a capacitor is used to block low-frequency or DC signals when wired in series. However, an inductor can be used in parallel to pass off low frequencies to ground, while letting high frequencies pass through.

In both of these situations, if the currents going to ground will be significant at all, you might also consider putting a small resistor in the parallel circuit as well. This will lessen the ability of the circuit to pass signals off to ground, but will also prevent short circuit behavior if you get significant signals being shunted off to ground.

Additionally, when you switch from the inline to the parallel version of these circuits, you wind up wasting the power that gets shunted off to ground. In the series versions of the circuit, any unused power is either blocked or stored. Therefore, it doesn't really waste much power. However, in the parallel versions, the filtered power is simply sent to ground, essentially wasting it.

Review

In this chapter, we learned:

1. A resistor-inductor series circuit is known as an RL circuit.
2. RL circuits have time constants very similar to RC circuits.
3. The time constant for an RL circuit is given by *dividing* the inductance by the resistance.
4. For RL circuits, the voltage and current values for each time constant are swapped.
5. Inductors and capacitors can be used to filter specific frequencies.
6. Capacitors allow high-frequencies to go through, while inductors allow lower frequencies to go through.
7. Using capacitors and inductors together allow a person to define a specific range of frequencies that they wish to either block or allow.
8. Radios use this feature which allow people to filter only the specific radio station frequency they want.
9. Capacitors and inductors can be used for the others' job in filters by wiring them in parallel so that they carry their type of current (AC or DC) to ground instead of letting it pass to the load.

Apply What You Have Learned

1. What is the time constant of a series circuit consisting of a $50\,\Omega$ resistor and a $2\,\mathrm{H}$ inductor?
2. What is the time constant of a series circuit consisting of a $10\,\Omega$ resistor and a $5\,\mu\mathrm{H}$ inductor?
3. If I have a $9\,\mathrm{V}$ battery and I connect it to a series circuit consisting of a $1\,\mathrm{k}\Omega$ resistor and a $23\,\mu\mathrm{H}$ inductor, how much time will it take before the current through the inductor reaches approximately 87% of its maximum value?
4. If I have a $5\,\mathrm{V}$ source and I connect it to a series circuit consisting of a $2\,\mathrm{k}\Omega$ resistor and a $6\,\mu\mathrm{H}$ inductor, how much time will it take before the voltage across the inductor falls below $0.25\,\mathrm{V}$.
5. If I have a circuit that has unwanted high-pitched noise, what component can I wire in series with the circuit to remove the noise?
6. If I have a circuit that has unwanted high-pitched noise, what component can I wire in parallel with the circuit to remove the noise?
7. What types of currents does an inductor (a) block and (b) allow?
8. What types of currents does a capacitor (a) block and (b) allow?
9. If I am building a radio, I need to allow through only very specific frequencies. What component or combination of components would I use to do this?

Chapter 23

Reactance and Impedance

23.1 Reactance

We have discussed resistance quite a bit in this book. Resistance is specifically about the ability of a component to be a good conductor of electricity. When a circuit encounters resistance, power is lost through the resistor.

However, another way of preventing current from flowing is known as *reactance*. With reactance, the power isn't dissipated, but rather the current is *prevented from flowing altogether*.

Let's think again about what happens when a voltage is connected to a capacitor in series. The capacitor starts to fill up. As the capacitor gets more an more full, there is less charge that can get onto the plate of the capacitor. This prevents the other side from filling up as well, and current cannot get through the capacitor. This acts *in a similar way to resistance*—it is preventing (impeding) the flow of current. However, it is not dissipating power because it is actually preventing the current from flowing. This is known as **reactance**. For capacitors it is called **capacitative reactance** and for inductors it is called **inductive reactance**.

Reactance is usually frequency-dependent. Again, going to the capacitor example, with high frequencies, the capacitor is continually charging and discharging, so it never really gets full, so it never impedes the current flow very much. Therefore, capacitors add very little reactance with high-frequency AC current. The lower frequencies, however, give the capacitor time to get full, and when they are full, they impede the current flow. Therefore, for capacitors, lower frequencies create more reactance.

Reactance is measured in ohms, just like resistance. However, they cannot be simply added to resistances, so they are usually prefixed with the letter j. So, 50 ohms of reactance is usually labelled as $j50\,\Omega$ so that it is understood as a reactance. Reactances can be added to each other and resistances can be added to each other. We will see how to combine them in Section 23.2. Reactances are using denotated using the letter X.

The reactance of a capacitor (X_C) is given by the following formula:

$$X_C = -\frac{1}{2\pi \cdot f \cdot C} \tag{23.1}$$

In this formula, f is the AC frequency of the signal (in hertz) and C is the capacitance. It might seem strange that this produces a negative value. The reason for this will make sense as we go forward. However, it is *not* producing negative impedance—we will see this when we combine reactance with resistance.

Example 23.21 What is the reactance of a 50 nF capacitor to a signal of 200 Hz?

To find this, we merely use the formula:

$$\begin{aligned} X_C &= \frac{1}{2\pi \cdot f \cdot C} \\ &= \frac{1}{2\pi \cdot 200 \cdot 0.00000005} \\ &\approx \frac{1}{2 \cdot 3.14 \cdot 200 \cdot 0.00000005} \\ &= \frac{1}{0.00000624} \\ &\approx -j160256\,\Omega \end{aligned}$$

You can see from this formula why it is said that a capacitor blocks DC current. DC current is, essentially, current that does not oscillate. In other words, the frequency is zero. Therefore, the formula will reduce to $\frac{1}{0}$, which is infinite. Therefore, it has infinite reactance against DC current.

Also note what happens as the frequency increases. As the frequency increases, the denominator gets larger and larger. That means that the reactance is getting smaller and smaller—closer and closer to zero. As the frequency goes up, the reactance is essentially heading towards zero, but will never get there because the frequency can't be infinite.

The formula for **inductive reactance** (X_L) is very similar:

$$X_L = 2\pi \cdot f \cdot L \tag{23.2}$$

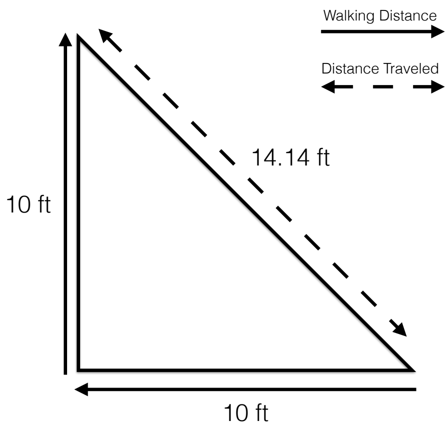
In this equation, f is the signal frequency and L is the inductance of the inductor in Henries.

Example 23.22 Let's say that I have an 3 H inductor with a 50 Hz AC signal. How much reactance does the inductor have in this circuit?

$$\begin{aligned} X_L &= 2\pi \cdot f \cdot L \\ &= 2 \cdot 3.14 \cdot 50 \cdot 3 \\ &= j9420\,\Omega \end{aligned}$$

The reactance in this circuit is $j9,420\,\Omega$.

Figure 23.1: Total Distance Traveled vs. Total Displacement



23.2 Impedance

In fact, resistance and reactance are usually added together in a circuit to get a quantity known as **impedance**, which is simply the combination of resistive and reactive quantities. Impedance is often designated using the letter Z.

Resistance and reactance aren't added together directly, instead you can think of them acting at angles to each other. Let's say that I start at my house and walk ten feet out my front door. Then, I turn 90 degree right and walk another ten feet. While I have walked twenty feet, I am *not* twenty feet from my door. I am, instead, a little over 14 feet from my door. I can call this my displacement. Figure 23.1 shows what this looks like visually.

Since this is a right triangle, the distance from the start to the end is found on the hypotenuse of this triangle. We can calculate the total displacement using the Pythagorean theorem ($A^2 + B^2 = C^2$). If we solve for C (total displacement), we get:

$$C = \sqrt{A^2 + B^2} \tag{23.3}$$

So, in our distance example, if I went forward 10 feet, turned left, and went another 10 feet, the total distance traveled would be:

$$
\begin{aligned}
C &= \sqrt{A^2 + B^2} \\
&= \sqrt{10^2 + 10^2} \\
&= \sqrt{100 + 100} \\
&= \sqrt{200} \\
&\approx 14.14
\end{aligned}
$$

The total impedance is like the total distance from your door. Resistance and reactance are like different walking directions (at right angles to each other), and impedance is the total displacement. That's why we use the letter j to signify an impedance—it is just like resistance but in a different direction.

So how doe we calculate impedance? In fact, it is calculated *precisely like* the displacement calculation in Equation 23.3:

$$\text{impedance} = \sqrt{\text{resistance}^2 + \text{reactance}^2} \tag{23.4}$$

Or, using their common abbreviations, we can say:

$$Z = \sqrt{R^2 + X^2} \tag{23.5}$$

Let's see how we can use Equation 23.4 to calculate total impedance. If I have a circuit that has $30\,\Omega$ of resistance and $j20\,\Omega$ of reactance, then the formula for total impedance is:

$$
\begin{aligned}
\text{impedance} &= \sqrt{\text{resistance}^2 + \text{reactance}^2} \\
&= \sqrt{30^2 + 20^2} \\
&= \sqrt{900 + 400} \\
&= \sqrt{1300} \\
&\approx 36.1\,\Omega
\end{aligned}
$$

As you can see, when using this formula we are calculating a total impedance, so the j drops away.

Example 23.23 If I have a $1\,\mathrm{k\Omega}$ resistor in series with a $100\,\mathrm{nF}$ capacitor with a $800\,\mathrm{Hz}$ signal, what is the total impedance to the signal that my circuit is giving?

To find out impedance, we need both resistance and reactance. We already have resistance—$1\,\mathrm{k\Omega}$. The reactance is found by using Equation 23.1:

$$\begin{aligned}
X_C &= -\frac{1}{2\pi \cdot f \cdot C} \\
&= -\frac{1}{2\pi \cdot 800 \cdot 0.0000001} \\
&\approx -\frac{1}{0.0005024} \\
&\approx -j1990\,\Omega
\end{aligned}$$

So the reactance is about $-j1990\,\Omega$.

So, if the resistance is $1000\,\Omega$ and the reactance is $-j1990\,\Omega$ what is the impedance? The impedance is found by using Equation 23.4:

$$\begin{aligned}
\text{impedance} &= \sqrt{\text{resistance}^2 + \text{reactance}^2} \\
&= \sqrt{1000^2 + (-1990)^2} \\
&= \sqrt{1000000 + 3960100} \\
&= \sqrt{4960100} \\
&\approx 2227\,\Omega
\end{aligned}$$

23.3 RLC Circuits

So far we have discussed RC (resistor-capacitor) and RL (resistor-inductor) circuits. When you combine all of these components together, you get an RLC (resistor-inductor-capacitor) circuit.

When you calculate the impedance of such circuits, you have to be sure you include the reactance of *both* the capacitative and the inductive components. While inductors and capacitors both offer reactance to certain frequencies, their reactances actually oppose each other. That is, the reactance of one cancels out the reactance of the other. This is why the capacitative reactance is negative and the inductive reactance is positive.

Therefore, when calculating reactances that include *both* inductance and capacitance, you can add the reactances just like you would add resistances. However, since the capacitive reactances are negative and the inductive reactances are positive, they wind up canceling each other out to some degree.

Example 23.24 If I have an inductor of 5 mH and a capacitor of 5 µF in series with a $200\,\Omega$ resistor, what is the impedance of the circuit for a frequency of 320 Hz?

To solve this problem, we need to first find the capacitative reactance (X_C) and the inductive reactance(X_L). To get the capacitative reactance, we use Equation 23.1:

$$\begin{aligned} X_C &= -\frac{1}{2\pi \cdot f \cdot C} \\ &= -\frac{1}{2\pi \cdot 320 \cdot 0.000005} \\ &\approx -\frac{1}{0.01} \\ &\approx -j100\,\Omega \end{aligned}$$

The inductive reactance is found using Equation 23.2:

$$\begin{aligned} X_L &= 2\pi \cdot f \cdot L \\ &= 2\pi \cdot 320 \cdot 0.005 \\ &\approx j10\,\Omega \end{aligned}$$

Now, we can just add these reactances together.

$$\begin{aligned} X_{total} &= X_L - X_C \\ &= j10\,\Omega + -j100\,\Omega \\ &= -j90\,\Omega \end{aligned}$$

The fact that this is negative is not a problem because it will be squared (which will get rid of the negative) in the next step. Now that we know the resistance ($200\,\Omega$) and the reactance ($-j90\,\Omega$), we just need to use Equation 23.4 to calculate the total impedance:

$$\begin{aligned} \text{impedance} &= \sqrt{\text{resistance}^2 + \text{reactance}^2} \\ &= \sqrt{200^2 + (-90)^2} \\ &= \sqrt{40000 + 8100} \\ &= \sqrt{48100} \\ &\approx 219\,\Omega \end{aligned}$$

So the total impedance (opposition to current) in this circuit is $219\,\Omega$.

23.4 Ohm's Law for AC Circuits

In an AC circuit, the current and voltage are continually varying. Therefore, using the traditional Ohm's law, you would have to calculate Ohm's law over and over again in order to find out the relationships between voltage, current, and resistance.

However, there is a form of Ohm's law that works directly on AC circuits of a given frequency. That is, it is essentially a *summary* of the voltages and currents that happen on each cycle. Ohm's law for AC circuits is basically identical to the previous Ohm's law, but the terms are slightly different:

$$V_{RMS} = I_{RMS} \cdot Z \tag{23.6}$$

Here, the voltage we are referring to (V_{RMS}) is an *average* voltage through one cycle of AC. This average is known as the **RMS** average. It is a little different that the typical average you might think of. If an AC voltage is swinging back-and-forth from positive to negative, the actual average voltage is probably around zero. However, RMS voltage is about calculating the average amount of push in any direction—positive or negative. Therefore, the RMS voltage will always yield a positive answer.[1]

Likewise, the current refers to the RMS current (I_{RMS}). Just like the RMS voltage, the RMS current will always be positive, because it is the measure of the average amount of flow in *any* direction.

Finally, the impedance Z is calculated as we have noted in this chapter—by combining resistances and reactances together into an impedance.

Thus, Ohm's law for AC circuits can be used to express summary relationships about average voltage, average current, and impedance in an AC signal.

Example 23.25 I have an AC circuit whose RMS voltage is 10 V. I have calculated the impedance of this circuit to be 20 Ω. What is the RMS current of this circuit?

To find this out, we just rearrange Ohm's law a little bit:

$$\begin{aligned} V_{RMS} &= I_{RMS} \cdot Z \\ I_{RMS} &= \frac{V_{RMS}}{Z} \end{aligned}$$

Now I just use the values given to fill in the blanks:

$$I_{RMS} = \frac{V_{RMS}}{Z} \qquad = \frac{10}{20} = 0.5\,\mathrm{A}$$

In this circuit we would have an average of half an amp (500 milliamps) flowing through the circuit.

Example 23.26 I have an AC voltage source with an RMS voltage of 5 V running at 200 Hz. It is connected in series with a 50 kΩ resistor and a 50 nF capacitor. What is the current in this circuit?

[1] RMS stands for "root mean square." It is obtained by (a) squaring every data point, (b) averaging the squares, and then (c) taking the square root of the average. This is why it will be positive—it deals in squares.

To find this out, we have to first find the total impedance of the circuit. That means we have to use Equation 23.1 to find the reactance of the capacitor:

$$\begin{aligned} X_C &= -\frac{1}{2\pi \cdot f \cdot C} \\ &= -\frac{1}{2 \cdot 3.14 \cdot 200 \cdot 0.00000005} \\ &= -\frac{1}{0.00000628} \\ &\approx -j159236\,\Omega \end{aligned}$$

Now that we have the resistance ($50\,\mathrm{k}\Omega$) and the reactance ($-j159236\,\Omega$) we can combine them with Equation 23.5:

$$\begin{aligned} Z &= \sqrt{R^2 + X^2} \\ &= \sqrt{50000^2 + 159236^2} \\ &= \sqrt{2500000000 + 25356103696} \\ &= \sqrt{27856103696} \\ &\approx 166901\,\Omega \end{aligned}$$

Now we can use Ohm's law for AC circuits (Equation 23.6 to find the current:

$$\begin{aligned} I_{RMS} &= \frac{V_{RMS}}{Z} \\ &= \frac{5}{166901} \\ &\approx 0.00003\,\mathrm{A} \end{aligned}$$

This means that the average current (I_{RMS}) will be approximately 0.00003 A, or 30 µA.

23.5 Resonant Frequencies of RLC Circuits

As we have seen, the capacitative reactance goes closer to zero when the frequency goes up. Likewise, the inductive reactance increases when the frequency goes up. Additionally, the capacitative reactance and the inductive reactance have opposite signs—negative for capacitative reactance and positive for inductive reactance).

What is interesting is that if you have a combination of inductors and capacitors, there is always some frequency at which their reactances exactly cancel each other out. This point is known as the **resonant frequency** of the circuit.

When a capacitor and an inductor are in series with each other, it is termed an LC series circuit. Because the inductor inhibits high frequencies and the capacitor inhibits low frequencies, LC circuits can be used to let through a very specific frequency range. The center of this range is known as the **resonant frequency** of the circuit.

Now, if you are good with algebra, you can combine Equation 23.1 and Equation 23.2 to figure out the resonant frequency of a circuit (i.e., set them to add up to zero and then solve for the frequency f). However, to spare you the trouble, there is a formula that you can use to find the resonant frequency of a circuit:

$$f = \frac{1}{2\pi\sqrt{L \cdot C}} \tag{23.7}$$

At this frequency, there is no total reactance to the circuit—the only impedance comes from the resistance.

Example 23.27 Let's say that you have a 20 µF capacitor in series with a 10 mH inductor. What is the resonant frequency of this circuit?

To find the resonant frequency, we only need to employ Equation 23.7:

$$\begin{aligned} f &= \frac{1}{2\pi\sqrt{L \cdot C}} \\ &= \frac{1}{2\pi\sqrt{0.01 \cdot 0.00002}} \\ &= \frac{1}{2\pi\sqrt{0.0000002}} \\ &\approx \frac{1}{2\pi \cdot 0.000447} \\ &\approx \frac{1}{0.00279} \\ &\approx 358\,\text{Hz} \end{aligned}$$

Therefore, this circuit has a resonant frequency of 358 Hz. This means that, at this frequency, this circuit has no reactive impedance.

Resonance frequencies are important in signal processing. They can be used in audio equipment to boost the sound of a specific frequency (since all other frequencies will have resistance). They can be used to select radio stations in radio equipment (since it will be the only frequency allowed through without resistance). You can also remove a specific frequency by taking a resonant frequency circuit to ground, thereby having a specific frequency short-circuited to ground with no resistance.

Review

In this chapter, we learned:

1. Reactance (X) is a property of some electronics components that is similar to resistance, but it *prevents* the flow of current instead of *dissipating* the flow (i.e., converting it to heat).
2. Reactance, like resistance, is measured in ohms. A j is placed in front of the reactance to specify that it is a reactance value.
3. Reactance is frequency-dependent—the amount of reactance depends on the frequency of the signal.
4. Capacitors and inductors each have formulas that can be used to calculate the reactance of the components.
5. Capacitors year negative reactance and inductors yield positive reactance. This means that their reactances will oppose and cancel each other out to some degree.
6. Impedance (Z) is the total inhibition of the flow of current, combining both resistive and reactive elements.
7. Reactance and resistance are combined into impedance in the same way that walking two different directions can be combined into a total distance from your originating point—using the Pythagorean theorem.
8. RMS voltage (V_{RMS}) is the average voltage of an AC circuit, regardless of the direction (positive or negative) of the voltage. This can be used to summarize the effects of an AC voltage.
9. RMS current (I_{RMS}) is the average current of an AC circuit, regardless of the direction (positive or negative) of the voltage. This can be used to summarize the effects of an AC current.
10. Ohm's law for AC circuits yields the summary relationship between RMS voltage, RMS current, and impedance in an AC circuit. It is identical to the previous Ohm's law, but uses the summary values for the circuit at a particular frequency, rather than the values at a particular point in time.
11. The resonant frequency of a circuit is the frequency at which inductive reactance and capacitative reactance cancel each other out.
12. Resonant frequencies can be used in any application where isolating a frequency is important, because the resonant frequency will be the only frequency not encountering resistance.

Exercises

1. As the frequency of a signal goes up, how does that affect the reactance from a capacitor? What about with an inductor?
2. As the frequency of a signal goes down, how does that affect the reactance from a capacitor? What about with an inductor?
3. What is true about the relationship between the capacitative reactance and the inductive reactance at the resonant frequency?
4. Why is power not used up with reactance?
5. How are reactance and resistance combined to yield impedance?
6. Calculate the capacitative reactance of a 3 F capacitor at 5 Hz.
7. Calculate the capacitative reactance of a 20 µF capacitor at 200 Hz.
8. Calculate the inductive reactance of a 7 H inductor at 10 Hz.
9. Calculate the inductive reactance of a 8 mH inductor at 152 Hz.
10. Calculate the impedance of a circuit with a 200 Ω resistor in series with a 75 µF capacitor with a signal of 345 Hz.
11. Calculate the impedance of a circuit with a 310 Ω resistor in series with a 90 nF capacitor with a signal of 800 Hz.
12. Calculate the impedance of a circuit with no resistor and a 60 mH inductor with a signal of 89 Hz.
13. Calculate the impedance of a circuit with a 50 Ω resistor in series with a 75 µH inductor with a signal of 255 Hz.
14. If I have an AC circuit with an RMS voltage of 6 V and an impedance of 1 kΩ, what is the average (RMS) current of this circuit?
15. If I have an AC circuit, and I measure the AC voltage as 10 V RMS, and I measure the AC current at 2 mA RMS, what is the impedance of this circuit?
16. If I have an 80 Hz AC circuit that has an 8 V RMS voltage source in series with a 500 Ω resistor, a 5 H inductor, and a 200 nF capacitor, what is the RMS current flowing in this circuit?
17. Calculate the impedance of a circuit with a 250 Ω resistor in series with a 87 µH inductor and a 104 µF capacitor with a signal of 745 Hz.
18. What is the resonant frequency of the circuit in the previous question?
19. What is the reactance of a circuit at its resonant frequency?
20. If I have a 10 µF capacitor, what size inductor do I need to have a resonant frequency of 250 Hz?

Part IV

Amplification Circuits

Chapter 24

DC Motors

Chapter 25

Amplifying Power with Transistors

Amplification is the conversion of a low-power signal to a higher-power signal. Normally when we think of amplification we think of sound amplifiers for musical instruments. Indeed those are amplifiers, and we will build a sound amplifier later in this book. However, *anytime* you convert a low-power input to a higher-power output you have amplified the signal, whether that was a DC signal or an AC signal. In this chapter, we will focus on amplifying DC signals.

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 ATmega328/P (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 output (whether current, voltage, or power) than these can provide. 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.

Another scenario to consider is a situation where we want to control a high-power motor or other device from a button or switch. Sometimes it can be problematic to have a switch for a device have high power run through it. It could be dangerous, or it could cost money. Let's say that we had a switch that we wanted to control a high-power device that was 1,000 feet away. If we had the full power running through the switch, that means that we have to run larger cables, and will have to account for the large resistance in the wires. Running power across that distance will result in power loss because of the resistance in the wires, which will increase the cost for running the unit! However, if we instead use a low-power circuit to run the switch, we don't get nearly as much power loss. We just need to *amplify* the power output of the switch to control our device one the signal reaches it. The amount of amplification that occurs is known as the **gain** of an amplifier.

25.1 An Amplification Parable

As we noted in Chapter 11, 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 himself 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) by adjusting the dam (the physical resistance against the water). Thus, he *amplified* the effects of his actions by controlling the resistance on the higher-powered current.

25.2 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 smaller-powered electric signal to control a higher-powered electric signal by adjusting resistance.

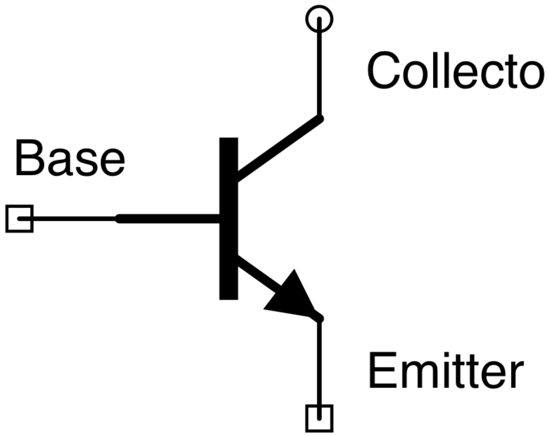
Another way you can think of it as like an outdoor faucet—the water going through the faucet is controlled by the wheel knob on the top, which provides a variable amount of resistance to the flow. The faucet can be fully-on, fully-off, or somewhere in-between, all based on where the knob is set. The knob setting is like the input current—a specific level of input current will control the amount of flow that comes out.

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 flow of electricity between the other two.

The main way that the types of transistors differ is in whether the knob on the faucet is controlled by voltage or by current. 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).

FETs are very interesting because their inputs read voltage levels without consuming any current. However, their usage is somewhat difficult for a number of reasons. First of all, they don't provide nearly as much gain as BJTs. Secondly, BJTs are much more stable and linear in the way that they operate. FETs are

Figure 25.1: The Schematic Symbol for a Transistor



more complicated to use correctly, and depend a lot more on understanding their physics than BJTs do. Many modern integrated circuits have switched to using FETs for their inputs since the power consumption is greatly reduced. **CMOS** chips are chips that use FET technology to limit the power consumption inside the chip. Some of these, however, still use BJTs to provide the final output stages if they need higher output gain. This book focuses on BJTs because they have a simpler conceptual operation.

BJTs come in two basic forms based on whether the knob is normally closed but turned on by positive current (an NPN transistor) or whether the knob is normally open but closed off by positive current (a PNP transistor). In this book, we will focus on NPN BJT transistors.

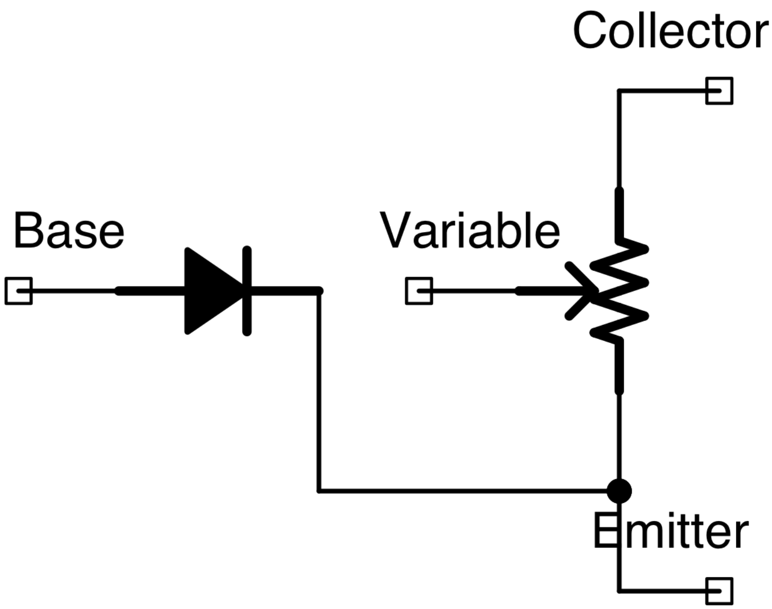
25.3 Parts of the Transistor

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 facuet), 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 25.1 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 25.2 shows a conceptual picture of how the transistor operates. The connection from the base to

Figure 25.2: A Conceptual View of Transistor Operation



the emitter operates as a diode, and the connection from the collector to the emitter operates as a variable resistor, offering resistances from zero (completely open dam) to infinity (completely closed dam). The resistance of the variable resistor is based on the current flowing through the base. The variable resistor is adjusted so that, under certain conditions, the *current* flowing from collector to emitter is a certain multiple of the current flowing from the base to the emitter.

When we talk about the voltages and currents flowing through the resistor, there are special names you need to remember and keep in mind. Each of the legs of the transistor are named by the first letter of their role. The Collector is C, the Emitter is E, and the Base is B. Then, each of the voltages currents are labelled based on which leg they are going from and to. Therefore, V_{BE} is the voltage difference between the base and the emitter, while V_{CE} is the voltage difference between the collector and the emitter and V_{CB} is the voltage difference between the collector and the base. I_{BE} is the current flowing between the base and the emitter and I_{CE} is the current flowing between the collector and the emitter. The total current coming out of the emitter is $I_{BE} + I_{CE}$. Take time to think about these designations as we are going to be using them extensively when we talk about transistors and their usage in a circuit.

A photo of a transistor can be seen in Figure 25.3. This is the transistor we will focus on in this book—the 2N2222A (sometimes called the PN2222A). It is important to read the data sheet to find out information about your transistor—especially to know which transistor leg is which! For the picture in Figure 25.3, the

Figure 25.3: A 2N2222A Transistor in a TO-92 Package

collector is on the right, the base is in the middle, and the emitter is on the left. Note that some other transistors have *different* pin configurations, which is why it is so important to check the data sheets. For instance, the P2N2222A (very similar name!) has the collector and emitter pins reversed!

Transistors can also come in a variety of shapes and sizes, known as **packages**. The package depicted in Figure 25.3 is known as a TO-92 package. Other packages you might see are a TO-18 package (looks like a tiny metal cylinder), or in a package similar to an integrated circuit.

25.4 NPN Transistor Operation Basics

To fully understand NPN transistor operation requires a lot of complicated mathematics. However, you can get a "good enough" understanding of it just by remembering a few simple rules.

Rule 1: The Transistor is Off by Default

By default, if there is no current flowing in the base, there will be no current flowing from the collector to the emitter. NPN transistors default to an "off" state.

Rule 2: V_{BE} Needs to be $0.6\,\mathrm{V}$ to Turn the Transistor On

Remember that there is essentially a diode connecting the base to the emitter. Diodes have a voltage drop of about $0.6\,\mathrm{V}$. Therefore, once the base voltage rises to $0.6\,\mathrm{V}$ *above* the emitter voltage, the transistor will turn on and current will start to flow.

Rule 3: V_{BE} Will Always be Exactly 0.6 V When the Transistor is On

This is a corollary of the previous rule. Remember from Chapter 9 that we used diodes to give us fixed voltage differences between points on a circuit. This is the same in a transistor. Because the BE junction acts as a diode, the base will always be 0.6 V above the emitter while the transistor is turned on.

Rule 4: The Collector Should Always Be More Positive than the Emitter

While technically you can have the collector go below the voltage of the base or the emitter, it is generally a bad idea with NPN transistors. It makes the circuit much harder to analyze. This book will assume that the circuit is setup in this manner.

Rule 5: When the Transistor is On, I_{CE} is a Linear Amplification of I_{BE}

So, when the transistor is on, the transistor amplifies the *current* flowing from the base to the emitter by adjusting the floodgates between the collector and the emitter. The multiplier that the transistor amplifies by is known as the transistor's **beta**—this is the current gain that an NPN transistor provides. The symbol for this value can be either β or h_{FE}. The problem with a transistor's beta is that it isn't very exact or very constant. A batch of "identical" transistors can have betas that vary quite a bit. And, while they are operating, their temperature and other environmental factors will affect the beta as well. There are things you can do to compensate for this, but for now just realize that it happens. While there are transistors with a wide variety of ranges of their betas, the most common NPN transistors have a beta of around 100.

The exceptions to this are in Rules 6 and 7.

Rule 6: The Transistor Cannot Amplify More than the Collector Can Supply

This is mostly a reminder that the amplification comes *from* the collector current. If the collector can't supply the amplification, it won't happen. Basically, we need to think of the transistor as controlling a resistor from the collector to the emitter which will adjust itself to maintain the ratio (beta) between the base-emitter current and the collector-emitter current. Thus, it can't provide less resistance than no resistance.

Rule 7: If the Base Voltage is Greater than the Collector Voltage, the Transistor is Saturated

If the base voltage rises above the collector voltage, this causes the transistor to behave as if there was no resistance going from the collector to the emitter. This is known as **saturation mode**.

Using these rules, thinking about transistor action is fairly straightforward. In the next section, we are going to put these rules into practice.

Figure 25.4: Using a Switch at the Start of a Circuit

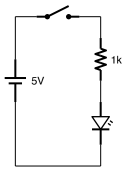
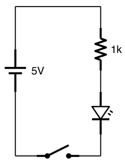


Figure 25.5: Using a Switch at the End of a Circuit



25.5 The Transistor as a Switch

One of the issues with transistors is that it takes a while before using a transistor becomes intuitive. Transistors, as we will see in the forthcoming chapters, wind up needing a lot of special considerations. Because of this, many people don't use transistors directly, and instead choose to only use integrated circuits (see Chapter 12). Integrated circuits, since they are based on the needs of a circuit instead of simple physical properties, tend to be much easier to work with. Most of the guess work has been taken out, and the chips are built so that they can be inserted into a circuit in a straightforward way. Even though some people opt to use integrated circuits instead of using transistors directly, it is worthwhile to understand their operation. It is always better to choose an option because you understand your available alternatives instead of choosing an option because that choice is the only one you understand.

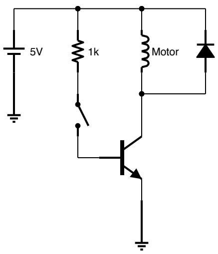
Now, when we think of buttons and switches, most people naturally put the switch at the *beginning* of the circuit that is being turned on or off. Figure 25.4 shows what this looks like. However, it is just as valid to place the switch at the end, as shown in Figure 25.5.

When using transistors as a switch, we almost always place them at the *end* of a circuit. The reason for this should become clear as we examine circuits.

The first circuit we will look at is Figure 25.6. In this circuit, there is no real *need* for a transistor—we could just as easily have put the switch where the transistor is. However, understanding how this setup works will help us understand other transistor circuits. In this circuit, the base is controlled by a small signal (the size of the signal is set by the size of the resistor). When the base turns on, it switches on the connection from the collector to the emitter, which controls current to the motor (the diode is simply a snubber diode as described in Chapter 21).

If the emitter of a transistor is simply connected directly to ground as it is in this example, the easiest way to

Figure 25.6: Using a Transistor as a Switch for a Motor



analyze the circuit is by looking at the flow of current through the base. When the switch is closed, current will flow from the voltage source, through the resistor, across the transistor to ground. How much current? Well, this is actually a simple question. Remember that the junction from the base to the emitter can be treated as a simple diode (Rules 2 and 3). Therefore, we have a very simple circuit to analyze—voltage source to resistor to diode to ground. The voltage source is 5 V and we have a diode (0.6 V) in the circuit path, so the voltage going through the resistor will be 4.4 V. Since the resistor is a 1 kΩ resistor, then, using Ohm's law, the current will be $I = \frac{V}{R} = \frac{4.4}{1000} = 0.0044\,\text{A}$, or 4.4 mA.

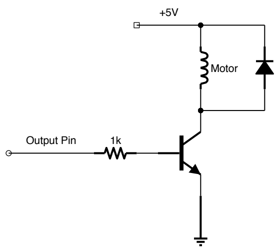
Since the current going through the base (I_{BE}) is 4.4 mA, how much current is flowing from the collector to the emitter. We will assume for our exercises that the beta of transistors is exactly 100. According to Rule 5, that means that the current going from the collector to the emitter is 100 times the base current. Therefore, the current going from the collector to the emitter must can be determined by $I_{CE} = \beta \cdot I_{BE} = 100 \cdot 4.4 = 440\,\text{mA}$. Therefore, the current going from the collector to the emitter is 440 mA. Because the current at the collector is 440 mA, that means that the current going through the motor is also 440 mA.

Depending on the current we *wanted* flowing through the motor, we could choose other resistor values to set the current to the appropriate level. However, because of Rule 6, the collector current will be limited by the motor's characteristics as well.

So, why did we put the transistor at the end of the circuit? Let's imagine that we added one component to the circuit—a resistor after the emitter before the ground. All of a sudden, the circuit is a lot harder to analyze. Why? Well, we can no longer determine the base current by simply looking at the current path through the base. The voltage across that final resistor will *not* be based on the base current, but based on the *combined* current from both the base and the collector. Thus, when there are components after the emitter, in order to analyze the base current, you have to analyze how the components after the base respond to the *combined* current of the base and collector, but we won't know that until *after* you calculate the base current. It is *possible* to do this, but the math isn't fun. Instead, by connecting the emitter *directly* to ground, we simplify our calculations because we *know* the voltage after the emitter—since it is connected to ground it will be zero.

Thus, by connecting the emitter directly to ground, we can analyze the current flow from the base *independently* of the current flow from the collector. Additionally, connecting the emitter to ground will automatically make sure our DC circuits follow Rule 4, and makes it easy to analyze when the transistor turns on and off by Rule 2.

Figure 25.7: Using a Transistor to Control a Motor with a Microcontroller



Just as we have looked at several common resistor circuit patterns, there are also several common transistor circuit patterns. The type of circuit we are looking at in this chapter is known as a **common emitter** circuit. This is because the "interesting" parts of the circuit are at the base (which provides the current to be amplified) and the collector (where the preceding circuit enjoyed the amplified current), and the emitter is connected to a common reference point (the ground in this case).

25.6 Connecting a Transistor to an Arduino Output

To understand *why* we would use a transistor for a switch in the first place, let's imagine that we have a motor just like in Figure 25.6, but in this case we want it to be controlled by an output pin from an Arduino running on an ATmega328/P.

Now, on this chip, output pins put out 5 V but their current rating maxes out at 40 mA. However, motors usually require much more current than that. If we wanted our motor to use as much current as in Figure 25.6, it would blow out the chip if we tried to connect it directly to the output.

However, we can instead wire the output of the Arduino to the base of a transistor. Then, the current coming out of the Arduino will be *much smaller* than the current used by the motor.

Figure 25.7 shows how this is configured. The schematic for this setup is almost identical to that of Figure 25.6. The only difference is that the electrical output of the Arduino is being used to control the base current instead of a mechanical switch.

25.7 Stabilizing Transistor Beta With a Feedback Resistor

As we mentioned earlier, the transistor's beta is not a very stable parameter. If we mass-produced something with a transistor, each device would wind up having a transistor with a different beta. Additionally, as the device was used, the beta would *drift*, meaning that things such as the temperature of the transistor would affect the beta, so it wouldn't even have the same value the entire time it was turned on!

In order to get around this, engineers have developed ways of stabilizing the *actual* gain of a circuit even when the transistor's beta shifts. The way that this is achieved depends greatly on the type of circuit used. In a common emitter circuit like the one we have been looking at in this chapter, we can add a resistor to the emitter to stabilize the transistor's gain. I know that I *just said* not to do this because it is hard to analyze the effects. However, if you add a single resistor to the emitter, other people have worked out the math for you in order to make this work easily.

Now, to imagine *why* adding a resistor to the output stabilizes the transistor beta, we have to think about what happens when you do this. Without the resistor, when the transistor beta increases, it simply increases the current flow at the collector. Since the emitter is connected to ground, there aren't any more real effects. However, if I add a resistor to the emitter, then increasing the current flow at the collector will *also* increase the voltage at the emitter. Now, since the voltage between the base and the emitter (V_{BE}) *must* be at 0.6 V, this will actually *reduce* the current in the base.

This is known as **feedback**—where the *output* of the circuit comes back in some way to affect the input. Sometimes, feedback occurs because the output is wired back to the input, but in this case, the resistor simply increases the voltage at the emitter, causing the base to pull back.

What the final effect of adding a resistor to the base will do is to *limit* the gain of the transistor to a *fixed* value that won't change as the transistor beta changes. Additionally, the computation for this is very simple. So, if your transistor beta varies between 50 and 200, you can add a resistor to the emitter which will limit the actual transistor gain below 50, and it will keep this value very stable even as the transistor's beta drifts. In such a configuration, the most stable gain you can get for a given transistor beta is about $\frac{1}{4}$ of the transsitor's lowest beta.

Now, the equation for this varies with each type of circuit. The following equation is for the type of transistor circuit covered in this chapter, which has a simple DC resistance coming into the base of a common emitter NPN transistor DC amplifier. We will call the resistance at the base R_B, and the size of the resistor that we are going to add at the emitter as R_E.

What we will do is the following:

1. Pretend that the transistor has a fixed beta value somewhere below its specifications (at most $\frac{1}{4}$ of the transistor's specified beta). We will call this value K. The lower K you choose will result in a more stable operating point but with less gain.
2. Design the common emitter circuit given this fixed beta value *without* the emitter resistor. Do *all* calculations without the emitter resistor.
3. After the circuit design is complete, add up the total resistances coming into the base of the transistor (in the circuits in this chapter, it is just a single resistor). We will call this value R_B.
4. Now we need to determine the value of the emitter resistor (R_E). The value is simply $R_E = \frac{R_B}{K}$.
5. Simply add in the emitter resistor between the emitter and the ground. No need to calculate anything else.

So, if we used a transistor whose beta is between 100 and 200, and we wanted to be sure that the gain was limited to 25 ($\frac{1}{4}$ of the low end of the beta), we can simply, after calculating everything for a beta of 25, add in an emitter resistor that is $\frac{1}{100}$th of the base resistance.

Figure 25.8: Stabilizing Transistor Gain with Emitter Resistor

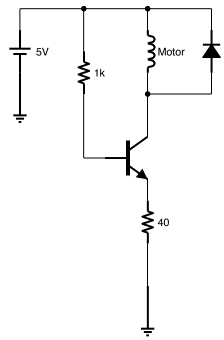


Figure 25.8 shows this in action. This is the same circuit as Figure 25.6, but with an emitter resistor which will keep the gain from traveling above 25 even as the beta of the transistor rises.

You may be wondering *how* the equation for calculating the size of the emitter resistor came about. It isn't fancy, it is just very long. However, if you are interested, the details can be found in Section E.4.

25.8 A Word of Caution

One thing to keep in mind with transistors is that they can get very hot! Transistors have a maximum current rating, and that often is based on the amount of heat that they are able to dissipate. Transistors that are able to handle large currents are called **power transistors**, and usually have an attachment for a **heat sink**, which helps it dissipate heat to the air more efficiently.

If you build a circuit similar to the one in this chapter, be sure to keep in mind both the specs of the motor (how much voltage and current is required for it to operate) and the specs of the transistor (how much current the transistor can handle). If the motor doesn't have enough voltage or current it might not turn on, and if the transistor can't handle the current it could easily burn out.

If you wanted to see inductive kick in action, you can replace the diode in the circuit with an LED. Every time you let go of the button, the LED will light up for a moment.

Review

In this chapter, we learned:

- It is often beneficial to be able to control a high-power signal using a low-power signal.
- The two major types of transistors are bipolar junction transistors (BJTs) and Field-Effect Transistors (FETs).
- BJTs are current-controlled devices and FETs are voltage-controlled devices.
- The terminals of a BJT transistor are the base (B), the collector (C), and the emitter (E).
- Voltages and currents going through a transistor are labeled using the terminals that the current is passing through. For instance, I_{BE} refers to the current flowing between the base (B) and the emitter (E), and V_{CE} refers to the voltage difference between the collector (C) and the emitter (E).
- BJTs come in two main configurations—NPN and PNP.
- With NPN transistors, a small positive current at the base causes a larger current to flow from the collector to the emitter.
- With PNP transistors, current at the base reduces the current flow from collector to the emitter.
- NPN transistors can be analyzed using these seven rules:
    1. The transistor is off by default.
    2. V_{BE} needs to be 0.6 V to turn the transistor on.
    3. V_{BE} will always be *exactly* 0.6 V while the transistor is turned on.
    4. The collector should always be more positive than the emitter.
    5. When the transistor is on, I_{CE} is a linear amplification of I_{BE}.
    6. The transistor cannot amplify more than the collector can supply.
    7. If the base voltage is greater than the collector voltage, the transistor is saturated (it will offer no resistance from the collector to the emitter).
- The amount of current amplification a transistor provides is known as the transistor's beta (also known as β or $h_F E$).
- The actual beta of a transistor is not very stable, and fluctuates quite a bit both within manufacturing and with environmental changes such as temperature.
- When used as a switch, transistors are usually placed at the *end* of a circuit in order to make the circuit analysis easier.
- Transistors are often used to couple the outputs of devices with low current limits (such as a microcontroller) with devices that require higher output currents (such as motors).
- To stabilize a transistor circuit's gain so that it doesn't vary with the transistor's beta, you can add in an emitter resistor.
- For the amplifier described in this chapter, if K is your desired stabilized gain and R_B is your base resistance, the emitter resistor should be $\frac{R_B}{K}$.

Apply What You Have Learned

Unless otherwise specified, assume that the transistor is a BJT NPN transistor and that the beta is stable.

1. If the base of a transistor is at 3 V and the transistor is on, what will be the emitter voltage?
2. If the base of a transistor is at 45 V and the emitter is on, what will be the emitter voltage?
3. If the base of a transistor is at 5 V and the emitter, if conducting, would have to be at 4.5 V, is the transistor on or off?
4. If the base of a transistor is at 0.6 V and the emitter is at ground, is the transistor on or off?
5. If the base of a transistor is at 0.4 V and the emitter is at ground, is the transistor on or off?
6. If a transistor has a base current (I_{BE}) of 2 mA and the transistor has a beta of 55, how much current is going through the collector (I_{CE})?
7. In the previous problem, how much total current is coming out of the emitter?
8. If a transistor has a base current of 3 mA and the transistor has a beta of 200, how much current is going through the collector?
9. If the base voltage is greater than the collector voltage, what does this mean for our transistor operation?
10. The output of your microcontroller is 3.3 V and supports a maximum output current of 10 mA. Using Figure 25.7 as a guide, design a circuit to control a motor that requires 80 mA to operate. Assume that the transistor beta is 100.
11. Redesign the previous circuit so that it utilizes a stabilizing resistor on the emitter to prevent variations in the transistor beta.

Chapter 26

Transistor Voltage Amplifiers

In Chapter 25 we started our study of the BJT NPN transistor. We noted that what the transistor actually amplified was *current*, so that the current coming into the collector was a multiple (known as β) of the current coming into the base.

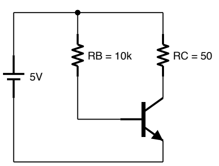
Even though what a transistor *does* is provide current amplification, in this chapter we will learn how to transform that into voltage amplification.

26.1 Converting Current into Voltage with Ohm's Law

If the transistor provides us with current amplification, how might we translate an amplification in the amount of current into an amplification in the amount of voltage? The answer is simple—Ohm's Law describes the relationship between current and voltage: $V = I \cdot R$. Therefore, a current amplification can be transformed into a voltage amplification if we use a resistor! The larger the resistor, the larger the change in voltage drop that a given change in current will induce for that resistor.

To see that happening take a look at the circuit in Figure 26.1. Note that this circuit on its own is rather useless, but it is helpful for illustrating how the calculations work. In this circuit, the current at the base

Figure 26.1: A Simple Current-to-Voltage Amplifier



is controlled by the resistor R_B. This current will drive be amplified into an increased current from the collector. However, the current at the collector is driven through a resistor, R_C. Because this is through a resistor, that means that Ohm's law will take effect, and the size of the voltage drop across R_C will depend on the current running through it.

Remember, Ohm's law states that $V = I \cdot R$, so any increase in current will increase the voltage drop across R_C, at least until the voltage at the collector is equal to the base voltage (which, in this circuit, is 0.6 V). If that happens, there is nothing more the transistor can do—it will just treat the collector-emitter junction as a short circuit.

Let's calculate to see what our circuit is actually doing. The voltage across the base is 5 V − 0.6 V = 4.4 V (remember—we have to account for the diode-like voltage drop in the transistor from the base to the emitter). Therefore, using Ohm's law, we can calculate the base current at $I = V/R = 4.4/10000 = 0.0004$ A.

Let's assume the transistor beta is 100. Therefore, the current flowing at the collector will be $0.0004 \cdot 100 = 0.040$ A. So, the voltage drop across the resistor can be calculated using Ohm's law. $V = I \cdot R = 0.040 \cdot 50 = 2$ V.

No, let's say that we change R_B so that we have more current running in the transistor. Let's increase R_B from 10 kΩ to 6 kΩ. Now the base current will be $I = V/R = 4.4/6000 = 0.000733$ A. Now the current flowing at the collector will be $100 \cdot 0.000733 = 0.0733$ A. So the voltage drop across the resistor is now $V = I \cdot R = 0.0733 \cdot 50 \approx 3.67$ V.

When we increase the current, we increase the voltage drop across the resistor. You may be wondering what happens to the extra voltage. That is, since the emitter of the resistor is at ground, and the voltage across R_C keeps changing, where is the remainder of the voltage? The transistor essentially swallows it up (technically, it dissipates it as heat).

Remember in our model of the transistor in Figure 25.2, the transistor acts as a variable resistor for the collector current. Therefore, the rest of the voltage drop happens *within* the transistor.

So, in effect, what we are doing is to use the resistor R_C to translate changes in current at the base into changes in the voltage drop across R_B.

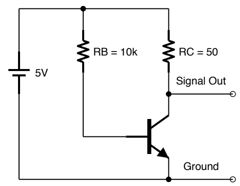
As you might have noticed, when dealing with transistors, the place where the "action" occurs is not always right where you might expect it. In this circuit, the location where the voltage amplification *actually occurs* is at a resistor (R_C) connected to the collector.

Example 26.28 In the circuit given, what is the voltage across the resistor if the base resistor R_B goes up to 20 kΩ?

$$\begin{aligned} I_B &= 4.4/20000 = 0.00022\,\mathrm{A} \\ I_C &= 100 \cdot I_B = 100 \cdot 0.00022 = 0.022\,\mathrm{A} \\ V_{R_B} &= I_C \cdot R_B = 0.022 \cdot 50 \approx 1.1\,\mathrm{V} \end{aligned}$$

Just to see where we are going, eventually we will use small voltage changes in the base to trigger current changes in the base which will then be amplified into a larger change in the voltage across R_B.

Figure 26.2: Reading the Amplified Signal from a Voltage Amplifier



26.2 Reading the Amplified Signal

So, we have managed to create a voltage drop which changes in response to changes in current at the base. But how do we read this voltage drop? It is rather difficult to read it directly, but we can read its *inverse* directly.

Take a look at Figure 26.2. In this figure, we added some output signal lines to show where we would read the output of the amplifier (i.e., where we would connect the rest of the circuit that receives the amplification). We put the output line *between* the collector resistor R_C and the transistor. What this will do is give us the voltage of the source voltage (5 V) *minus* the voltage across R_C. So, when we have a large voltage across R_C, that will be reflected in a low voltage in our output. Likewise, when there is a low voltage across R_C, that will be reflected in a high voltage in our output.

This sort of an output is known as an **inverted output**, because the output voltage is essentially reverse-amplified. That actually works just fine for audio signals, as it does not matter to the listener if the signal is inverted or not. However, if we needed to get it back to the non-inverted form, we could just add another amplification stage onto the end (we will see how to do this in Section 26.4).

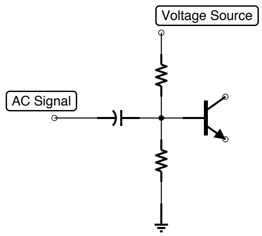
Having said all that, I should point out that we still don't know how to amplify an audio signal—yet. That is coming in the next section.

26.3 Amplifying an Audio Signal

What we really want to do is to amplify an audio signal. Imagine that someone is singing into a microphone, and we want to amplify the signal we get so that we can send it to a speaker. How would we do that?

There are a number of problems that you have to solve in order to get this done. You might imagine that you could just connect a microphone to the base of the transistor, and just amplify directly. That's a good idea, but sadly life is not always that easy. To understand why, remember that audio signals are basically alternating current. That means that the signal will swing both positive *and* negative. Also remember that the base voltage has to remain *above* the emitter voltage, and the emitter is tied to ground. Therefore, if we tried to do this, we would lose the bottom (negative) half of the signal. In fact, if it was a small signal, we might lose the *entire* signal if it never reached the required 0.6 V above ground.

Figure 26.3: Components of a Transistor Biasing Circuit



26.3.1 Biasing the Transistor Base Current

So what do we do? Well, what we want to do is to add a DC offset to the audio signal so that its midpoint is no longer zero volts, but close to the middle of the range where the transistor operates well. Adding a DC voltage is called **biasing** the signal. We are moving the midpoint of the signal to the point where the transistor will always be responding to it.

A bias circuit is simply a voltage divider that, in addition to a signal coming out, also has a signal coming in. Figure 26.3 shows the basic outline of what a transistor biasing circuit looks like. The main feature is a voltage divider which sets the bias voltage. The audio signal is coupled into the voltage divider through a capacitor. The capacitor is important because it couples together the unbiased AC signal with the biased AC signal. It performs the same function as the coupling capacitor in our tone generator (Section 20.5) but in reverse. It allows an alternating (AC) current to *feed into* a DC bias circuit.

Without the capacitor to couple the signals together, the voltage divider would likely send all of the current from the top resistor into the audio source, since it would be at a lower voltage than the bottom resistor! Thus, instead of biasing the signal, the top resistor would actual just send current through your microphone or other audio source. This is not really the result we want!

Instead, we use a capacitor to couple together our AC source and our DC bias circuit. Let's think about how this works in a circuit. When your circuit first turns on, the capacitor will charge up to the voltage divider voltage. Then, variations in the audio signal will push and pull charge onto the negative side of the capacitor, which will push and pull charge through the positive side of the capacitor. Note that if you use an electrolytic (i.e., polarized) capacitor, the positive side of the capacitor should be on the same side as the voltage divider. When the charge is pushed through the capacitor, that results in an increased current through the base of the transistor (although some of the additional current will also leak out through the resistor). The increase of the current through the base is then amplified using increased current in the collector.

So, in this scenario, what values should we use for the components? For the capacitor, we need a capacitor large enough so that audio frequencies don't encounter a lot of resistance. You can use Equation 23.1 from Chapter 23 to see how much reactance the capacitor will have at various frequencies, but for audio frequencies 10 µF is usually a good choice.

As for the resistors, if the voltage divider is too stiff (i.e., the resistors are too small), then the current coming in from the audio signal will have less influence—most of it will leak out through the bottom resistor. If we make our voltage divider looser (i.e., higher resistance values), then the signal from the audio source will have a much stronger influence on the current going through the base of the transistor, which is exactly what we want.

However, we don't want the signal current to swing the final current too much, either. Since this is AC current, if the total current (bias current + signal current) ever causes the bottom resistor to drop below 0.6 V, the transistor will turn off, and we will get clipping.

So, we have given a lot of considerations for how to setup your bias circuit, and you may be wondering how to fulfill them. Here is a basic process you can follow for creating your transistor bias circuit:

1. Find out how much current your source (microphone, antenna, etc.) will produce. The likely value will be well below a milliamp.
2. Pick a "no signal" current, known as the **quiescent** current for your base. This is the amount of current that will be flowing from your voltage divider before the signal is added in. This needs to be large enough to be sure that the current at the base will never totally swing negative, but small enough to prevent the current variations from the signal being drowned out by the quiescent current. 0.1 mA is usually a good starting value if you don't know what to pick (this is what we will use here).
3. Create a voltage divider which will (a) produce the given quiescent current with nothing coming in, and (b) have an output voltage that is about $10--20\%$ of the supply voltage plus the 0.6 V drop. This will keep the transistor conducting throughout the up-and-down swings of the input current. In our case, since we have a 5 V source, the voltage divider should give about a $1.1\,\mathrm{V}--1.6\,\mathrm{V}$ drop.

To achieve a 1 mA quiescent current, we need to have a total resistance of 5 kΩ. Because we are using such a small voltage (5 V), this means that the 0.6 V diode drop takes up a lot of our headroom, so we will probably want to use a 40 kΩ resistor (or the nearest value you have—the schematic calls for a 47 kΩ resistor because that is a fairly standard value) for the top resistor, and a 10 kΩ resistor for the bottom.

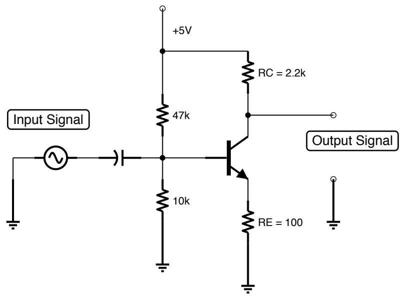
Note that there are other methods for biasing transistors, but using a voltage divider is a straightforward application of principles we have already learned in this book.

26.3.2 Choosing a Collector and Emitter Resistor

To choose the collector resistor (R_C), you need to think about how much voltage swing there will be. The most voltage we could have is our supply voltage—5 V. The least voltage we could have is 0.6 V before the transistor turns off. Therefore, to maximize the potential swings in voltage, we want to choose our quiescent (i.e., "no signal") voltage so that it hits right in the middle. That way, it has the most room to swing either direction.

Therefore, to reach the midpoing between 5 V and 0.6 V the resistor will need to drop 2.2 V. At the quiescent point, our base current is 0.1 mA. If our transistor's beta is 100, then our collector current will be 10 mA. If we want to clamp our transistor's amplification to 20 (to keep it from drifting), then the collector current

Figure 26.4: A Single-Stage Transistor Voltage Amplifier



will be 2 mA. Therefore, we need a resistor that drops 2.2 V with 2 mA. Using Ohm's law, we find that $R = V/I = 2.2/0.002 = 220$

As we mentioned earlier, the transistor beta is highly variable. So, if we wanted a configuration that was more stable (but with less gain), we can add a small emitter resistor to provide some negative feedback. If you add in an emitter resistor (R_E), you will limit your voltage gain to approximately $\frac{R_C}{R_E}$ (if you are interested in why this is the case, see Appendix E.5). So, if we wanted to limit our gain to around 20, we need to add in a small 10 Ω resistor to the emitter.

The final amplifier circuit is shown in Figure 26.4. Remember that the output is still DC biased, and therefore would need a coupling capacitor to go to audio equipment. However, depending on the audio source, the present amplifier may not have enough gain to be readily audible.

26.4 Adding a Second Stage

A single amplification stage is not always enough. If your signal source is weak enough, sometimes you need more power just to hear it. This can be accomplished in a number of ways. The simplest, conceptually, is to add another output stage to your amplifier.

In order to do this, we need to design the next stage to take into account the output of our first stage. We will need to use a coupling capacitor to handle the change in voltage from the output of the first stage into our bias circuit for the second stage. This needs to be a non-polarized capacitor, because of the potential for either side to be more positive than the other at any given moment (both sides are DC-biased, but the input has the potential to swing below the bias point of the next stage).

Figure 26.5 shows the complete two-stage amplifier. With this circuit, you can use most microphones and most headphones to get enough output power to hear yourself in your headphones. Figure 26.6 shows the two-stage amplifier built into a breadboard.

In this circuit, the quiescent point of both stages are set to the same value. This is because the initial source current is so low that a quiescent point high enough for the transistor to behave well is far above what is

Figure 26.5: The Complete Two-Stage Amplifier Circuit

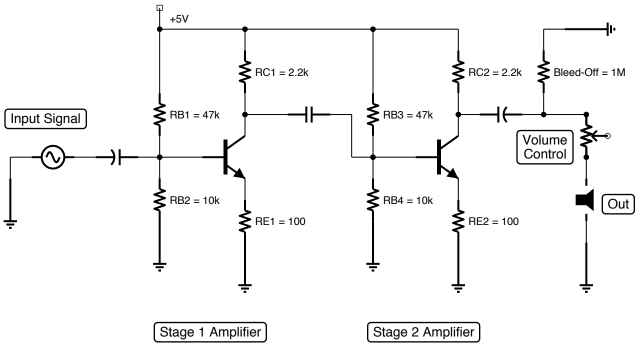
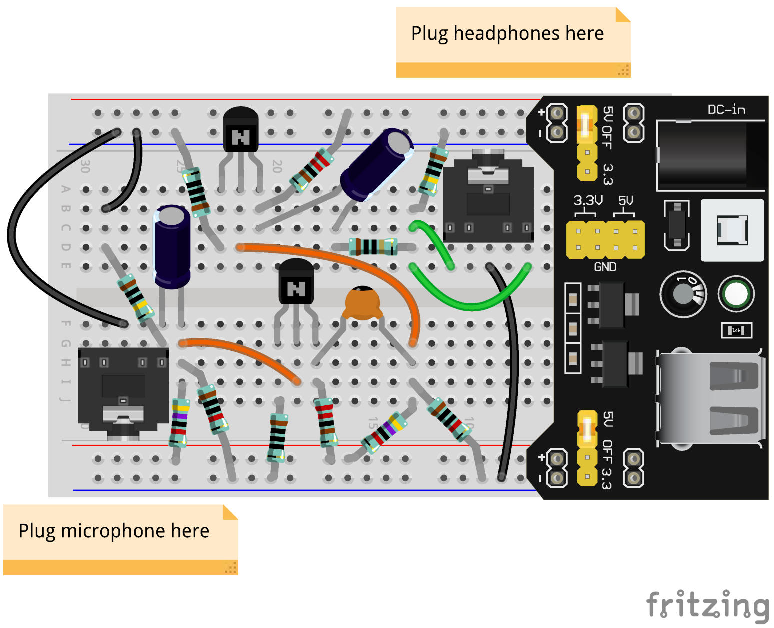


Figure 26.6: The Two-Stage Amplifier Built into a Breadboard



actually needed for the signal. Further amplification stages would require a higher quiescent current, because the signal is now large enough to overwhelm another bias stage of the same size. Additionally, not every stage must add to the voltage swing of the output. Once the voltage swings across the entire range, additional stages will add power (through increased current), not necessarily additional voltage. Nonetheless, that will still make it louder!

Also note that it may take a few seconds for the circuit to start operating after it is switched on. In the bias circuit, notice that there is both a resistor and a capacitor. This means that the bias circuit *also* forms an RC time circuit, which means that it will take a little time to get the bias circuit up to the proper voltage level.

One thing in this circuit we haven't discussed is the bleed-off resistors connected right next to the coupling capacitors for the input and output circuit. These are very large ($1,000,000\,\Omega$) resistors. They are large so that they do not have any effect on the calculations in the circuit itself, but they do provide a place for the negative side of the capacitor to drain out when nothing is connected. Otherwise, any residual charge on the capacitor has no place to go, and will remain even when the circuit is turned off and the devices are unplugged.

Designing transistor amplifiers can be tricky because there are a lot of things that can go wrong. Although there is some leeway, using the wrong resistors can result in distortion, or a loss of gain. Misconnecting a single component can render the entirety of the circuit inaudible.

If your bias circuit is too stiff (too high of a quiescent current), then the input signal won't have enough influence on the sound. If it is too weak, the sound will clip whenever the voltage drops too far. If the bias voltage is too low, the transistor won't conduct. If the bias voltage is too high, there isn't enough room for the voltage to swing. If the collector resistor is too large, the transistor will clip the signal when the current is at its highest. If the collector resistor is too small, the transistor will not sufficiently amplify your signal. If the emitter resistor is too large, you won't have enough gain, and if the emitter resistor is too small, your gain will be unstable (honestly, though, if you aren't getting enough gain, just connect your emitter directly to ground and don't worry about the stability so much). Some transistors also have quiescent currents which are more amenable to amplification than others. If the quiescent current is too low or too high, the transistor gain may be impacted. All of these also depend on knowing how much current your source will provide.

Because of these things, when building audio circuits, it is best to use an oscilloscope. An oscilloscope can help you visually see what the voltages look like at each point in your circuit. Oscilloscopes can cost as little or as much as you want them to. There are pocket oscilloscopes that you can purchase for less than a nice dinner out, and there are bench oscilloscopes that you would need several months salary to purchase. Any of those are helpful in analyzing your circuit.

Review

In this chapter, we learned:

1. Although transistors provide current amplification, current changes can be transformed into voltage changes using Ohm's law.
2. Using a resistor at the collector allows us to "read" a voltage change based on the changes in the currents going through the transistor.
3. Using a resistor in this way *inverts* the waveform—it will show low voltage when there is a lot of current, and high voltage when there isn't much current.
4. Adding in an emitter resistor limits the amount of voltage gain in the circuit to $\frac{R_C}{R_E}$ in order to compensate for variable/drifting transistor betas.
5. In order to amplify an audio signal, we have to add a DC bias to the signal so that the transistor stays in its operating range (positive voltage).
6. The simplest way to do use a transistor to amplify a signal is to add a voltage divider to the base of the transistor, with a coupling capacitor feeding the signal into the voltage divider.
7. The voltage divider should be designed to keep the transistor in its prime current/voltage range for amplification when the signal is neutral, and to keep voltage at the base above the 0.6 V level above the emitter no matter how far the signal swings negative. It also needs to be low enough that the collector never swings below it. Usually having the bias at $10--20\%$ of DC voltage works well.
8. The neutral, "no signal" design point is known as the quiescent point of a circuit. The quiescent point is the state of the circuit when the AC signal coming in is neutral (0 V).
9. Designing for a quiescent point simplifies the design process since all of the design considerations are simple DC considerations.
10. There are numerous ways to bias the base of a transistor, but a voltage divider is the simplest.
11. The AC signal is coupled into the voltage divider through a coupling capacitor in order to manage the difference between the pure AC signal and the DC biased signal.
12. The collector resistor should be chosen in order to place the quiescent output voltage right in the middle of the possible output range (i.e., quiescent collector current multiplied by the collector resistance should give you about half of the voltage range between voltage source and emitter voltage).
13. Weak AC signals often need multiple amplification stages to provide sufficient output power for driving outputs.
14. The output of one amplifier can be coupled through a capacitor into the input of a second amplifier.
15. If the signal sources and outputs are not permanently connected, adding a bleed-off resistor will enable the coupling capacitors to drain out after the jacks are disconnected.

16. There are numerous things that can go wrong in a transistor amplifier, including clipping the audio signal, having a bad quiescent current, or accidentally losing your gain, not to mention building the circuit wrong.

17. Because of the number of things that can go wrong, it is easiest to diagnose problems in an amplifier using an oscilloscope, which allows you to visualize what is happening at each point in the circuit.

Apply What You Have Learned

1. What is the purpose of the resistor in the collector of a transistor amplifier?

2. What is the purpose of the resistor in the emitter of a transistor amplifier?

3. Why is there a bias voltage on the base of the transistor? Why can't the signal just be connected in directly to the base?

4. Why is the signal coupled in through a capacitor?

5. Why does the single stage voltage amplifier discussed in this chapter invert its output?

6. If the output of the two-stage amplifier is coupled into a third stage, the signal current would swing 1.85 mA in either direction. Design a third amplification stage which can handle this amount of current.

Chapter 27

Examining Partial Circuits

We will end our discussion of amplification by discussing partial circuits. Often times you will need to design a circuit which connects to another circuit, either powering it or receiving power from it. For instance, in the amplification circuits from Chapter 26, the outputs were connected to a speaker. They could also be connected to another amplifier, or to a stomp box (a device to modulate the incoming signal in some way), or a recording circuit.

27.1 The Need for a Model

In order to connect circuits together, we need to be able to describe, in general terms, the ways that circuits fit together. In our early attempts to analyze circuits, we looked at how we could combine a lot of resistors in series and parallel to come up with a single resistance for the whole circuit.

When dealing with transistors and other power amplification devices, we often need to come up with a simplified model for how the input to a circuit or the output from a circuit behaves. Early on (in Chapter 8), we learned how to take multiple resistors in series and parallel and combine them into an equivalent single resistor.

When dealing with a power amplification circuit, it is often necessary look at various parts of the circuit by themselves, and figure out how they *look* to other parts of the circuit. The way that a partial circuit looks to other parts of the circuit is called the circuit's **Thévenin Equivalent** circuit.

A Thévenin equivalent circuit takes a partial circuit and reduces it to:

- A single voltage source (AC, DC, or DC-biased AC, expressed in RMS voltage)
- A single impedance (i.e., resistance) in series with the voltage source

Figure 27.1: A Complicated Circuit and its Thévenin Equivalent Circuit

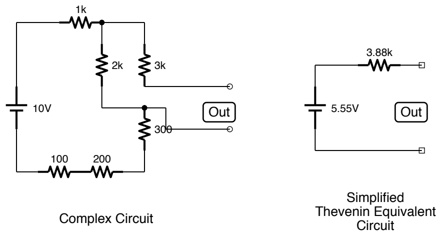
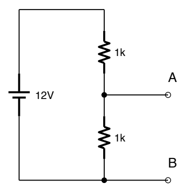


Figure 27.2: A Voltage Divider Partial Circuit



Note that the single voltage source may be *different* than the voltage source that is actually connected. What you are doing is see what the circuit looks like to another circuit. For instance, a voltage divider circuit makes the output of the voltage divider *look like* it is coming from a lower voltage source.

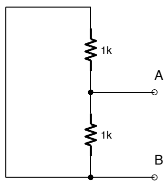
Figure 27.1 shows a circuit and its Thévenin Equivalent circuit. For purposes of thinking about and understanding the relationship between the circuit and things attached to the circuit, we can view the circuit as being the same as its Thévenin Equivalent. Thus, having a Thévenin Equivalent circuit greatly simplifies our modeling, calculating, and understanding of how circuits work together.

Any network of power sources and resistances can be converted into a Thévenin Equivalent circuit. You can also get a Thévenin Equivalent circuit for a circuit that includes capacitors and inductors, but the calculations become more difficult and the results are only valid for a specific frequency (each frequency will have a different Thévenin Equivalent circuit). For simplicity we will just focus on resistive circuits.

27.2 Calculating Thévenin Equivalent Values

To see how to calculate the voltage and resistance for a Thévenin Equivalent circuit, this section will take a classic voltage divider circuit and analyze how it "looks" to other attached circuits. Figure 27.2 shows an example of a partial circuit. Like most partial circuits, this circuit has two output points—A and B. What we are wanting to know is this—if we attach another circuit up to A and B, is there a model that we can use to understand how the other circuit "sees" our circuit? The goal of a making a Thévenin Equivalent circuit is to understand what our circuit will look like to other attached circuits.

Figure 27.3: Calculating the Thévenin Resistance of the Circuit



So, since our Thévenin Equivalent circuit will have a voltage source and a single resistor, we need to calculate what the voltage and resistance of this circuit will be. To calculate the voltage, find out what the voltage of the circuit at the output is when there is *nothing connected*. That is, if we were to leave A and B disconnected, and I were to connect my multimeter to A and B, what would the voltage be? This is your Thévenin voltage. Since this is a voltage divider, you can just use normal voltage divider calculations to find this out. In this case, we have a 12 V source, and the voltage divider divides it exactly in half (1 kΩ for each half). Therefore, the output voltage is 6 V. Therefore, our Thévenin Equivalent circuit will have a 6 V source.

Now we need to find our Thévenin resistance. There are multiple tricks to do this, but the simplest one is to replace all voltage sources in your circuit with a wire (i.e., a short circuit), and simply compute the total resistance between A and B.[1]

Figure 27.3 shows what this looks like. Therefore, to calculate the Thévenin resistance of this circuit, simply calculate the total resistance from A to B. In this case, there are two parallel paths from A to B—one through the first resistor and one through the second. Therefore, we add up the resistors as parallel resistances. As a result, our Thévenin resistance will be:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} \\ &= \frac{1}{\frac{1}{1000} + \frac{1}{1000}} \\ &= \frac{1}{0.001 + 0.001} \\ &= \frac{1}{0.002} \\ &= 500\,\Omega \end{aligned}$$

Therefore, we would say that this partial circuit has a Thévenin voltage of 6 V and a Thévenin resistance of 500 Ω. Whenever we attach a circuit to this circuit, what that other circuit will "see" is a circuit like the one in Figure 27.4.

If you wanted to prove this to yourself, you can imagine a variety of different circuits attached to both our

[1] We haven't talked about *current* sources much in this book. However, for completeness, I should note that if you have a current source, you should replace it with an open circuit (i.e., a gap in the wire) when calculating Thévenin resistance.

Figure 27.4: The Thévenin Equivalent of the Voltage Divider

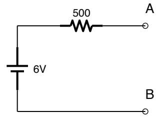
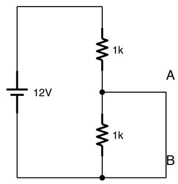


Figure 27.5: Finding the Short Circuit Voltage



original circuit and to the Thévenin Equivalent circuit. You will find that, in all cases, the amount of voltage and current the Thévenin Equivalent circuit provides to the other circuit is the exact same as what the original circuit will provide.

That isn't to say that the circuits themselves are exactly equivalent. Our original voltage divider uses up a lot of current stepping down the voltage of the voltage source. Not only does that waste energy from our battery, but it probably also causes a lot of heat. However, *the subcircuit that gets attached to A and B* will see both our original circuit and the Thévenin Equivalent circuit as providing the same output.

27.3 Another Way of Calculating Thévenin Resistance

There is another way of calculating Thévenin resistance. In this method, we first calculate what the current would be if you shorted A to B directly with a wire. This is known as the short-circuit current, or I_{SHORT}. Then, after calculating this, you can divide the Thévenin voltage by I_{SHORT} to obtain the Thévenin resistance.

When doing this, you have to remember that anything in parallel with our short will be essentially ignored—the current will always want to go through our short circuit.

Figure 27.5 shows what this looks like. What we want to do is to calculate the current going from A to B. Since A to B is a short circuit in parallel with our second resistor, we know that *all* of the current will prefer the short circuit. This means that the current going through A and B will simply be the current that is limited by the first resistor.

So, since we have a 12 V source and a 1 kΩ resistor, the short circuit current will be:

$$
\begin{aligned}
I_{SHORT} &= \frac{V}{R} \\
&= \frac{12}{1000} \\
&= 0.012\,\mathrm{A}
\end{aligned}
$$

Now, to determine the Thévenin resistance, we divide the Thévenin voltage by this number:

$$
\begin{aligned}
R_{Thevenin} &= \frac{V_{Thevenin}}{I_{SHORT}} \\
&= \frac{6}{0.012} \\
&= 500\,\Omega
\end{aligned}
$$

As you can see, this is the same value that we got from the previous method.

27.4 Finding the Thévenin Equivalent of an AC Circuit with Reactive Elements

If a circuit has reactive elements (inductors and capacitors), we have to do a little more work to find the Thévenin Equivalent circuit.

For DC circuits, this is relatively simple. Since capacitors block DC currents and inductors are a short circuit for DC currents, we can simply treat the capacitors as open circuits (i.e., unconnected) and treat the inductors as short circuits (simple wires). For AC circuits, you can get a feel for what this will be by assuming the opposite—that capacitors will be short circuits and inductors will be open circuits.

However, if you were to try to solve it explicitly, the problem is a little more difficult. The problem is that a full analysis of such circuits requires math involving complex numbers (i.e., numbers involving the imaginary unit i). While the technique is roughly equivalent to adding resistances in series and parallel as we have done before, it is much more difficult to do the math with complex numbers. For those who want to see this technique in action, I have included more discussion on this topic in Appendix **??**.

For the purposes of this book, the previous statements about DC and AC should suffice for a general understanding of how your circuit works. In this book will typically use this for analyzing circuits that are mixed between AC and DC signals—small AC signals with a DC offset. We will generally concern ourselves with the DC offset for purposes of computation.

27.5 Using Thévenin Equivalent Descriptions

Many circuits are described to users of that circuit using Thévenin Equivalent descriptions. For instance, many circuits are described by their input or output impedance. This gives you a rough guide to imagine what will happen if you connect your own circuit to such circuits. Imagine that you have a circuit that has a Thévenin Equivalent output impedance of $500\,\Omega$. If you connect an output circuit that only has $250\,\Omega$ of resistance, what do you think that will do to the signal? Well, since the output of the circuit is equivalent to going through a $500\,\Omega$ resistor (that's what Thévenin Equivalence means), then if I connect a $250\,\Omega$ resistor, then I will have created a voltage divider in which two thirds of the voltage will be dropped by the circuit I am connecting to, and I will only get one third of the output voltage. On the other hand, if my output circuit is $50,000\,\Omega$, then the voltage drop within the output circuit is negligible compared to the voltage drop within my circuit. This means that my circuit will essentially receive the full Thévenin Equivalent voltage.

We can also use this to calculate the amount of current that our circuit will draw. Let's say that a circuit yields a Thévenin Equivalent output of $4\,\mathrm{V}$ with an $800\,\Omega$ impedance. If I connect a $3,000\,\Omega$ output circuit, how much current will flow? The total resistance will be $3,800\,\Omega$, so the current will be $V/R = 4/3800 \approx 1.05\,\mathrm{mA}$.

The same is true for connecting an input circuit that you make to an output circuit someone else made. For instance, speakers and headphones are normally rated as an impedance—$8\,\Omega$, $16\,\Omega$, etc. They aren't, strictly speaking, resistors, but at normal audio frequencies they behave essentially like one—they have a Thévenin Equivalent impedance (their Thévenin Equivalent voltage is zero).

Example 27.29 If I have an output circuit which is Thévenin Equivalent to $3\,\mathrm{V}$ RMS and $200\,\Omega$, and I connect it to a set of $16\,\Omega$ headphones, what will the power of the headphones be in watts?

We can understand this circuit as simply being a voltage source followed by two resistors in series. The voltage source will be $3\,\mathrm{V}$ and the resistances will be $200\,\Omega$ and $16\,\Omega$, totalling $216\,\Omega$. The current will therefor be $V/R = 3/216 \approx 0.0139\,\mathrm{A}$. The voltage drop in the headphones will be $I \cdot R = 0.0139 \cdot 16 \approx 0.222\,\mathrm{V}$. Therefore the power delivered to the headphones will be $V \cdot I = 0.222 \cdot 0.0139 \approx 0.00309\,\mathrm{W}$, or $3.09\,\mathrm{mW}$.

27.6 Finding Thévenin Equivalent Circuits Experimentally

In addition to using circuit schematics to determine Thévenin Equivalent Circuits, it is also possible to determine them experimentally. This way, if you are unsure of the input or output characteristics of your device, you can measure it yourself. The problem with measuring it yourself is that it requires attaching a load to the circuit. Some circuits will fry if a wrongly-sized load is attached. You have been warned.

The easiest way to determine Thévenin Equivalency experimentally is rather unsafe, but it will help us understand better why the method works. Imagine a voltage divider where the bottom resistor has an extremely large resistance—say $100\,\mathrm{M}\Omega$. In such a voltage divider, the bottom resistor will have almost the entirety of the voltage drop, right? In fact, if the bottom resistor was infinite, it would in fact have all of the voltage drop.

Because of this, we can determine the Thévenin Equivalent voltage by measuring the output voltage when there is nothing connected, because no connection means that there is infinite resistance between the output and ground. Measuring this value will give us the Thévenin Equivalent voltage.

To determine the Thévenin Equivalent current, we can short-circuit the output. When doing this, the *only* impedances to the current will be within the device itself. Therefore, using Ohm's law, the amount of current this draws will tell us how large of a resistance the output is yielding.

Example 27.30 If I measure the open-circuit (i.e., disconnected) voltage of the output of an unknown circuit as 8 V and the short-circuit current of the output as 10 mA, what is the Thévenin Equivalent circuit?

To find this out, we simply use Ohm's law. What resistance would cause an 8 V source have 10 mA of current?

$$\begin{aligned} R &= V/I \\ &= 8/0.010 \\ &= 800 \end{aligned}$$

Therefore, our Thévenin Equivalent circuit is 8 V with an impedance of 800 Ω.

The problem with this method is that you don't normally want to short circuit your output. Additionally, some circuits require some sort of a load to work properly. In order to adjust to such scenarios, there is a set of equations that allow us to measure the voltage drop across a large and small resistance (instead of infinite and no resistance) and come up with a Thévenin Equivalent circuit.

The equations are a little complex, but you can actually derive them directly from Ohm's law if you work at it. The first one calculates the Thévenin Equivalent voltage (V_T) from the voltage with a high resistance (V_H), the high resistance value (R_H), the voltage with a low resistance (V_L), and the low resistance value (R_L):

$$V_T = \frac{\frac{V_H}{R_H}(R_H - R_L)}{1 - \frac{V_H R_L}{R_H V_L}} \tag{27.1}$$

Then, we can calculate the Thévenin Equivalent resistance:

$$R_T = \frac{V_T R_L}{V_L} - R_L \tag{27.2}$$

For a basic starting point, you can use 1 MΩ for the high resistance value, and 1 kΩ for the low resistance value.

Example 27.31 I have a circuit that generates an output for which I need to know its Thévenin Equivalent properties. I tested the circuit with a 200 Ω resistance and a 1000 Ω resistance. With the 200 Ω resistance, there was a 2 V drop across the resistance. With the 1000 Ω resistance, there was a 5 V drop across the resistance. What is the Thévenin Equivalent circuit for this circuit?

First we find the Thévenin Equivalent voltage using Equation 27.1:

$$\begin{aligned}
V_T &= \frac{\frac{V_H}{R_H}(R_H - R_L)}{1 - \frac{V_H R_L}{R_H V_L}} \\
&= \frac{\frac{5}{1000}(1000 - 200)}{1 - \frac{5 \cdot 200}{1000 \cdot 2}} \\
&= \frac{0.005 \cdot 800}{1 - \frac{1000}{2000}} \\
&= \frac{4}{0.5} \\
&= 8\,\text{V}
\end{aligned}$$

Next we can find the Thévenin Equivalent resistance using Equation 27.2:

$$\begin{aligned}
R_T &= \frac{V_T R_L}{V_L} - R_L \\
&= \frac{8 \cdot 200}{2} - 200 \\
&= 800 - 200 \\
&= 600\,\Omega
\end{aligned}$$

Therefore, our unknown circuit has a Thévenin Equivalent voltage of 8 V and a Thévenin Equivalent impedance of 600 Ω.

What makes this method valuable is that it allows a way to *experimentally* determine the Thévenin Equivalent of a partial circuit that you don't have a schematic for, or for which determining the Thévenin Equivalent circuit might be difficult due to non-linear components such as transistors.

Review

In this chapter, we learned:

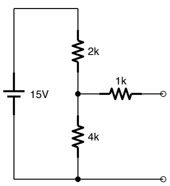
1. In order to be able to connect circuits together without knowing all of the details of how they are implemented, we need a simplified model of how those circuits work with other circuits they are connected to.
2. A Thévenin Equivalent circuit is a combination of a single voltage source and a single series impedance which models the way that the given circuit will respond to other attached circuits.
3. To calculate Thévenin Equivalent voltage, calculate the voltage drop for an open circuit between the two terminals. This is the Thévenin Equivalent voltage.
4. To calculate Thévenin Equivalent impedance, calculate the impedance from one terminal to another (or to ground if there is only one terminal), replacing any voltage sources with short circuits.
5. Alternatively, to calculate Thévenin Equivalent impedance, calculate the current flowing from one terminal to another if there was a short circuit between them. Then use Ohm's law to calculate the resistance.
6. Thévenin Equivalent circuits can be used to understand how the resistances of attached circuits will affect the signal coming out of or into a circuit.
7. Thévenin Equivalent circuits can also be found experimentally.
8. Thévenin Equivalent voltage can be determined by simply measuring the voltage drop of an open circuit across the terminals.
9. Thévenin Equivalent resistance can be determined by measuring the current flow of a short circuit across the terminals, though it isn't recommended.
10. Alternatively, given two different load resistances across the terminals, a Thévenin Equivalent circuit can be calculated using Equations 27.1 and 27.2.

Apply What You Have Learned

1. Why would we want to know what a circuit's Thévenin Equivalent circuit is?
2. What are the two components of a Thévenin Equivalent circuit?
3. Think about the two-stage amplifier that you built in Chapter 26. How would you go about finding the Thévenin Equivalent circuit as it is seen by the headphones?
4. Suppose I have a circuit where the output terminals have a 2 V drop when it is an open circuit, and have 2 mA of current flowing through it when it is a short circuit. Draw the Thévenin Equivalent circuit.

5. If I have a Thévenin Equivalent circuit of 4 V with an impedance of 400 Ω, what will be the voltage drop of the load if I attach a 2000 Ω resistor across the output?

6. If I have a Thévenin Equivalent circuit of 3 V with an impedance of 100 Ω, what will be the voltage drop, the current, and the power of the load if I attach headphones rated at 32 Ω?



7. Calculate and draw the Thévenin Equivalent circuit of the circuit below:

8. Suppose I have a circuit where, when I add a load of 350 Ω I get a 7 V drop, and when I add a load of 2000 Ω I get an 8 V drop. Calculate and draw the Thévenin Equivalent circuit.

Chapter 28

Going Further

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 6.242Œ$10^1$8 protons. The same number of electrons produces a charge of -1 coulomb. Coulombs are represented by the symbol C.

DC current See *direct current.*

direct current

electron current flow

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

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

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

neutron An uncharged particle in the nucleus of an atom.

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

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

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

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

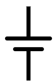
resistance Resistance measures how much a component resists the flow of electricity. Resistance is measured in ohms (Ω).

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

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

Appendix B

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 C

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.

C.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 12, 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 D

Electronics Equations and Where They Come From

This appendix is a catalog of equations in electronics and where they came from for those who are curious. This book is meant more for an introductory approach, but nonetheless many people are curious. This chapter isn't for the faint of heart, and it may involve lots of math you haven't taken. That's why it is stuck in an appendix.

However, if you are curious, these are the mathematical answers to your questions.

D.1 Basic Formulas

D.1.1 Charge and Current Quantities

- 1 coulomb = 6.241509Œ10^{1}8 electrons (how many electrons in a coulomb)
- $I = \frac{dC}{dt}$ (current is the derivative of charge with respect to time)
- $1A = 1\frac{C}{s}$ (A = ampere; C = coulomb; s = second)
- $3.6C = 1mAh$ (C = coulomb; mAh is milliamp-hour, a common unit for batteries)

D.1.2 Volt Quantities

Volts are basically measures of energy per unit of charge. Volts are also known as electromotive force (EMF), or ϵ. Volts can be expressed in a number of ways:

- $V = \frac{J}{C}$ (J = joules; C = coulombs)
- $V = \frac{\text{potential energy}}{\text{charge}}$
- $V = \frac{N \cdot m}{C}$ (N = newtons; m = meters; C = coulombs)
- $V = \frac{kg \cdot m^2}{A \cdot s^3}$ (kg = kilograms; m = meters; A = amperes; s = seconds)
- $V = \frac{d\phi}{dt}$ (Faraday's law of induction—voltage is the derivative of the flux of the magnetic field with respect to time)

D.1.3 Resistance and Conductance Quantities

Resistance is in ohm's. The inverse of resistance is conductance (the ability of current to flow through a wire) and is measured in Siemens (S). The Seimens unit is also called a mho (ohm spelled backwards), and is sometimes marked by an upside down omega ().

- $G = \frac{1}{R}$ (G = conductance in siemens, R = resistance)
- $G = \frac{I}{V}$ (G = conductance; I is current; V is voltage)
- $R = \frac{V}{I}$ (Ohm's law)

Individual materials have a resistivity (ρ).

$$R = \rho \cdot \frac{\text{length}}{\text{cross-sectional area}} \tag{D.1}$$

In other words, from beginning to end, resistance decreases with cross-sectional area, and increases with length.

D.1.4 Ohm's Law

V is voltage (in volts), I is current (in amperes), and R is resistance (in ohms).

$$V = I \cdot R \tag{D.2}$$

D.1.5 Power

P is in Watts. The following hold true for DC circuits. For AC circuits, they hold true if the resistance is actually an impedance.

- $P = V \cdot A$
- $P = I^2 R$
- $P = \frac{V^2}{R}$

D.1.6 Capacitance

Capacitance is the ability to store charge.

The fundamental equation for a capacitor:

$$Q = V \cdot C \tag{D.3}$$

Q is the amount of charge stored, V is the voltage across the terminals, and C is the capacitance in farads.

The derivative of this equation with respect to time is:

$$\frac{dQ}{dt} = \frac{dV}{dt} \cdot C \tag{D.4}$$

Because current is the derivative of charge, we can then say:

$$I = C\frac{dV}{dT} \tag{D.5}$$

The capacitance of capacitors is given by the equation:

$$C = \epsilon_r \epsilon_0 \frac{A}{d} \tag{D.6}$$

Here C is capacitance, ϵ_r is the dielectric constant of whatever separates the capacitor's plates, ϵ_0 is the dielectric constant of free space, A is the area of the plates in square meters, and d is the distance between the plates in meters.

D.1.7 Inductance

The fundamental equation for an inductor is:

$$\phi = L \cdot I \tag{D.7}$$

Here, ϕ is the flux of the magnetic field in Webers, L is inductance in henries, and I is current in amperes. The derivative gives you voltage:

$$\frac{d\phi}{dt} = L\frac{dI}{dt} \tag{D.8}$$
$$V = L\frac{dI}{dt} \tag{D.9}$$

In other words, the voltage produced is proportional to the change in current.

The inductance of a coil of wire can be calculated by:

$$L = \frac{\mu \cdot N^2 \cdot A}{l} \tag{D.10}$$

Where N is the number of turns of wire, A is the area of the coil, l is the length of the coil, and μ depends on the core being used.

D.2 Semiconductors

Components made from silicon are known as semiconductors, and have very useful non-linear properties.

D.2.1 Diodes

Diodes do not have a fixed voltage drop like we assume in this book. It is an exponential function, but is steep enough to act like a fixed 0.6 V voltage drop for most purposes. The actual equation is:

$$I = I_S(e^{\frac{V}{\eta V_T}} - 1) \tag{D.11}$$

I_S is the saturation current (depends on the construction of the diote), V is the voltage, η is either 1 for germanium or 2 for silicon, and V_T is known as the thermal voltage (the amount of voltage created just by particles moving around at a given temperature, usually about 0.026 V at room temperature).

D.2.2 NPN BJT Transistors

While we discussed general rules about BJT transistors, the technical model used to model them is known as the Ebers-Moll model.

D.3 555 Timer Oscillator Frequency Equation

In Chapter 19 we learned to make oscillators using the 555 timer chip. In the actual chapter, I wanted you to focus on actually learning what was happening with the 555 timer rather than using a formula. However, there is a nice, simple formula that allows you to relate the resistor/capacitor network of the 555 timer to the final output frequency.

The formula is as follows:

$$f = \frac{1.44}{C(R_1 + 2R_2)} \tag{D.12}$$

In this equation, f is the frequency, R_1 is the resistor coming from the supply voltage, R_2 is the resistor next to the capacitor, and C is the timer capacitor.

To understand where this equation comes from, remember that frequency is just $\frac{1}{\text{period}}$. We can use time constant formulas to find the period, and then just flip it to find the frequency.

If you recall, the period is just the total time it takes to complete a charge/discharge cycle. The 555 charges through *both* R_1 and R_2, but only discharges through R_2. Additionally, since it is just bouncing back-and-forth between $\frac{1}{3}$ and $\frac{2}{3}$ full, it only uses 0.693 time constants.

Therefore, we can have two formulas, one for the time charging and one for the time discharging:

$$\begin{aligned} T_{CHARGE} &= 0.693C(R_1 + R_2) \\ T_{DISCHARGE} &= 0.693CR_2 \end{aligned}$$

The total period is just these two time periods added together. Therefore, you get:

$$\begin{aligned} T_{PERIOD} &= 0.693C(R_1 + R_2) + 0.693CR_2 \\ &= 0.693C((R_1 + R_2) + R_2) && \text{Factoring out } 0.693C \\ &= 0.693C(R_1 + 2R_2) && \text{Regrouping} \end{aligned}$$

Since $f = \frac{1}{T_{PERIOD}}$, we can flip the above equation and get:

$$
\begin{aligned}
f &= \frac{1}{0.693C(R_1 + 2R_2)} \\
&= \frac{1}{0.693} \frac{1}{C(R_1 + 2R_2)} && \text{Regrouping} \\
&\approx 1.44 \frac{1}{C(R_1 + 2R_2)} \\
&= \frac{1.44}{C(R_1 + 2R_2)}
\end{aligned}
$$

At the end of the day, this is exactly what you did when you solved those problems, you just did it by hand instead of using a nice little formula. All a formula does is encapsulate the things that you normally do anyway, but simplifies it down to a set of pre-defined steps.

I have a love/hate relationship with formulas. Formulas are nice because they are easy to use. However, when you use them, it makes it easy to forget the basic facts behind them. The basic facts are more important than the formula, because you can rearrange the basic facts and develop all sorts of formulas depending on your needs. In fact, if you know the basic facts, and you know how to make formulas, if you ever forget a formula it is easy to determine one from the basic facts. Therefore, while memorizing formulas is important, knowing *why* formulas work is just as important, as it allows you to think more deeply and broadly and adapt your knowledge to new situations.

D.4 Current Gain Stabilization in BJT Common Emitter Applications

This section will show how we got the equation for the gain stabilizing emitter resistor you encountered in Chapter 25. We will need to imagine two circuits. One before we add the emitter resistor (we will call this the *nominal* circuit) and one after (we will call this the *actual* circuit). Since the goal is to do our calculations for base current on the circuit *without* the emitter resistor, we will call this current the *nominal base current*, and give it the symbol I_N. All other values and currents will be determined from the *actual* circuit. The final gain between the nominal base current we calculated and the final collector current we will designate as K. The values that are shared between the nominal and the actual circuit are V_S (source voltage) and V_B (base resistance).

$$
\begin{aligned}
K &= \frac{I_C}{I_N} && \text{this is our final gain} \\
I_N &= \frac{V_S - 0.6}{R_B} && \text{Ohm's Law for nominal base} \\
I_B &= \frac{V_S - V_B}{R_B} && \text{Ohm's Law for actual base} \\
V_B &= V_E + 0.6 && \text{transistor rules} \\
I_B &= \frac{V_S - (V_E + 0.6)}{R_B} && \text{substituting} \\
I_B &= \frac{V_S - V_E - 0.6)}{R_B} && \text{simplifying} \\
V_E &= R_E I_E && \text{Ohm's Law} \\
V_E &= R_E(I_B + I_C) && \text{substituting} \\
V_E &= R_E I_B + R_E I_C && \text{distributing} \\
I_B &= \frac{V_S - (R_E I_B + R_E I_C) - 0.6}{R_B} && \text{substituting} \\
I_B &= \frac{V_S - R_E I_B - R_E I_C - 0.6}{R_B} && \text{simplifying} \\
I_C &= \beta I_B && \text{transistor beta equation} \\
I_C &= \beta \frac{V_S - R_E I_B - R_E I_C - 0.6}{R_B} && \text{substituting} \\
I_C &= \frac{\beta V_S - \beta R_E I_B - \beta R_E I_C - \beta 0.6}{R_B} && \\
I_N &= \frac{V_S - 0.6}{R_B} && \text{Copied from Earlier} \\
K &= \frac{I_C}{I_N} && \text{This is the value we are looking for} \\
\frac{I_C}{I_N} &= \frac{\frac{\beta V_S - \beta R_E I_B - \beta R_E I_C - \beta 0.6}{R_B}}{\frac{V_S - 0.6}{R_B}} && \text{substituting} \\
\frac{I_C}{I_N} &= \frac{\beta V_S - \beta R_E I_B - \beta R_E I_C - \beta 0.6}{R_B} \frac{R_B}{V_S - 0.6} && \text{simplifying} \\
\frac{I_C}{I_N} &= \frac{\beta V_S - \beta R_E I_B - \beta R_E I_C - \beta 0.6}{V_S - 0.6} && \text{simplifying} \\
I_B &= \frac{I_C}{\beta} && \text{transistor beta definition} \\
\frac{I_C}{I_N} &= \frac{\beta V_S - \beta R_E \frac{I_C}{\beta} - \beta R_E I_C - \beta 0.6}{V_S - 0.6} && \text{substituting} \\
\frac{I_C}{I_N} &= \frac{\beta V_S - R_E I_C - \beta R_E I_C - \beta 0.6}{V_S - 0.6} && \text{simplifying}
\end{aligned}
$$

$$
\begin{aligned}
I_C(V_S - 0.6) &= I_N(\beta V_S - R_E I_C - \beta R_E I_C - \beta 0.6) && \text{cross-multiplying} \\
I_C V_S - 0.6 I_C &= I_N \beta V_S - I_N R_E I_C - I_N \beta R_E IC - I_N \beta 0.6 && \text{distributing} \\
I_C V_S - 0.6 I_C + I_N R_E I_C + I_N \beta R_E I_C &= I_N \beta V_S - I_N \beta 0.6 && \text{collecting } I_C \text{ terms} \\
I_C V_S - 0.6 I_C + \frac{V_S - 0.6}{R_B} R_E I_C + \frac{V_S - 0.6}{R_B} \beta R_E I_C &= I_N \beta V_S - I_N \beta 0.6 && \text{substituting some } I_N \text{ terms} \\
I_C V_S - 0.6 I_C R_B + V_S R_E IC - 0.6 R_E I_C + V_S \beta R_E I_C - 0.6 \beta R_E I_C &= R_B I_N \beta V_S - R_B I_N \beta 0.6 && \text{getting rid of fraction} \\
I_C(V_S - 0.6 R_B + V_S R_E - 0.6 R_E + V_S \beta R_E - 0.6 \beta R_E) &= I_N(R_B \beta V_S - R_B \beta 0.6) && \text{factoring} \\
\frac{I_C}{I_N} &= \frac{R_B \beta V_S - R_B \beta 0.6}{V_S - 0.6 R_B + V_S R_E - 0.6 R_E + V_S \beta R_E - 0.6 \beta R_E}
\end{aligned}
$$

Now, this looks like a huge mess, and it is. However, lets look at what happens with reasonable values. Let's say our base resistor was 1 kΩ and the emitter resistor was 300 kΩ. Let's also say that the source voltage if 5 V and the transistor β is 100. What does this look like?

$$
\begin{aligned}
\frac{IC}{IN} &= \frac{R_B \beta V_S - R_B \beta 0.6}{V_S - 0.6 R_B + V_S R_E - 0.6 R_E + V_S \beta R_E - 0.6 \beta R_E} \\
\frac{I_C}{I_N} &= \frac{1000 \cdot 100 \cdot 5 - 1000 \cdot 100 \cdot 0.6}{5 - 0.6 \cdot 1000 + 5 \cdot 300 - 0.6 \cdot 300 + 5 \cdot 100 \cdot 300 - 0.6 \cdot 100 \cdot 300}
\end{aligned}
$$

This then becomes

$$
\frac{I_C}{I_N} = \frac{500000 - 60000}{5 - 600 + 150000 - 180 + 1500 - 18000}
$$

Now, on the numerator, the dominating term is $500,000$, and on the bottom it is $150,000$. The other terms pale in comparison. This will be true for most "typical" situations. So, what makes up these two terms?

On the top, the $500,000$ term comes from $R_B \beta V_S$. On the bottom, the $150,000$ term comes from $V_S \beta R_E$. Therefore, a simplified look at this equation is just:

$$
\begin{aligned}
\frac{I_C}{I_N} &= \frac{R_B \beta V_S}{V_S \beta R_E} && \text{these are the dominant factors} \\
\frac{I_C}{I_N} &= \frac{R_B}{R_E} && \text{cancelling out factors}
\end{aligned}
$$

So, even though it isn't an exact result, you can see that the ratio between the actual current in the real circuit and the nominal base current that we calculated will be given by $\frac{R_B}{R_E}$.

D.5 Voltage Gain Stabilization in BJT Common Emitter Applications

The previous section told you how to stabilize the current gain from an emitter resistor, with the final gain being $\frac{R_B}{R_E}$. For *voltage* gain, the final gain is limited by $\frac{R_C}{R_E}$, and we will show that here using similar reasoning.

The voltage at the emitter and the base will be:

$$\begin{aligned} V_E &= I_E R_E \\ V_B &= V_E + 0.6 \\ V_B &= I_E R_E + 0.6 \end{aligned}$$

The voltage at the collector will be:

$$V_C = I_C R_C$$

However, the collector current and the emitter current are very close. Therefore, we can simplify this to say:

$$V_C = I_E R_C$$

We can then divide our equation for the collector voltage by our equation for the base voltage, and get:

$$\frac{V_C}{V_B} = \frac{I_E R_C}{I_E R_E + 0.6}$$

If we remove the diode voltage (which has relatively little influence overall), this simply becomes:

$$\begin{aligned} \frac{V_C}{V_B} &= \frac{I_E R_C}{I_E R_E} \\ &= \frac{R_C}{R_E} \end{aligned}$$

Therefore, the ratio of base voltage to output voltage is approximately equal to the ratio of collector to emitter. However, also keep in mind that this is the voltage *drop* in the collector. What we actually send to the output is actually our supply voltage with V_C subtracted from it.

As you can see, there is a lot of simplification involved. However, such simplifications allow us to think more clearly about our circuits. Since there are so many moving parts, looking for and finding the dominating factors is very important.

Note that this is important in life, too. Sometimes we get so enmeshed in the details that we forget what factors dominate our quality of life. Finding out what the important factors are help us to focus on the things that matter most, and let the details sort themselves out.

D.6 The Thévenin Formula

In Chapter 27, we used two formulas which allowed us to calculate the Thévenin Equivalent circuit for circuits experimentally. Equations 27.1 and 27.2 seem strange and complicated, but they are actually directly deducible from Ohm's law and the concept of an equivalent circuit.

The Thévenin Theorem states that any combinations of voltage sources and resistances can be replaced by a single voltage source and a single resistance. We will call this our Thévenin voltage source (V_T) and our Thévenin impedance (R_T). If we hook up a load (i.e., a fixed resistance) across the output terminals of this circuit, we will know the resistance that was added (because *we* added it), and we can measure the voltage drop across the resistor easily enough with a multimeter or oscilloscope.

We will need to measure this using two different loads because we have two unknowns—V_T and R_T. Using two different loads will give us two different equations using Ohm's law that will allow us to solve for two variables. We will call our lower-resistance load R_L and the voltage drop across the R_L resistor will be V_L. Likewise, our higher-resistance load we will call R_H and the voltage drop across it will be V_H. The current running through each of these loads (I_L and I_H) can be given by:

$$V_L = I_L \cdot R_L$$
$$V_H = I_H \cdot R_H$$

That is just simply Ohm's law. We can also use Ohm's law to develop equations for the whole circuit, including the Thévenin Equivalent voltage and impedance. Remember, because of the current rules, whatever current is flowing through our resistor must also be flowing in our Thévenin Equivalent impedance. Therefore, the Thévenin Equivalent voltage will be the current multiplied by the two impedances together. Therefore, this yields the following equations:

$$V_T = I_L(R_L + R_T)$$
$$V_T = I_H(R_H + R_T)$$

Both of these equations solve for V_T, given an unknown of R_T. We can also rearrange either of these to solve for R_T. Let's rearrange the first one to do that:

$$
\begin{aligned}
V_T &= I_L(R_L + R_T) && \text{Original equation} \\
\frac{V_T}{I_L} &= R_L + R_T && \text{Divide both sides} \\
\frac{V_T}{I_L} - R_L &= R_T && \text{Subtract } R_L \\
R_T &= \frac{V_T}{I_L} - R_L && \text{Solved for } R_T
\end{aligned}
$$

This is the same as Equation 27.2. However, it requires V_T to work. Now that we have an equation for R_T, we can substitute that back in and get an equation for V_T without using R_T. Using basic algebra manipulations, we can do the following:

$$
\begin{aligned}
V_T &= I_H(R_T + R_H) && \text{Original equation} \\
V_T &= I_H R_T + I_H R_H && \text{Distributive rule} \\
V_T &= I_H(\frac{V_T}{I_L} - R_L) + I_H R_H && \text{Substituting for } R_T \\
V_T &= I_H \frac{V_T}{I_L} - I_H R_L + I_H R_H && \text{Distributing} \\
V_T - I_H \frac{V_T}{I_L} &= -I_H R_L + I_H R_H && \text{Get the } V_T\text{s together} \\
V_T(1 - \frac{I_H}{I_L}) &= I_H(R_H - R_L) && \text{Factor both sides} \\
V_T &= \frac{I_H(R_H - R_L)}{1 - \frac{I_H}{I_L}} && \text{Divide both sides} \\
V_T &= \frac{\frac{V_H}{R_H}(R_H - R_L)}{1 - \frac{V_H R_L}{R_H V_L}} && \text{Replace currents with Ohm's law equivalents } (\frac{V}{R})
\end{aligned}
$$

As you can see, this is Equation 27.1.

Appendix E

Simplified Datasheets for Common Devices

FIXME—**need content**

YwRobot Power Module

Overview

This device allows you to supply power to your breadboard projects from a variety of sources through its barrel jack. The module down-steps the voltage to 5V or 3.3V (selectable with jumpers).

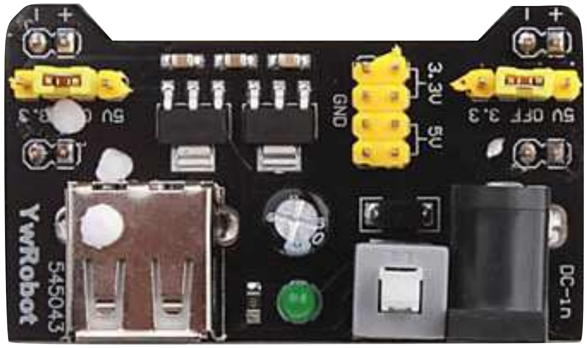
The power module comes with an on/off switch, and a set of header pins that can be used to wire power to other places.

The module is made to fit on a standard breadboard, where the output pins align directly onto the power rails of the breadboard.

Be sure to align the positive and negative markings on the module with their matching power rails!

Variations

- On some boards the USB jack can be used as an power input, and on some it is a power output only
- The “on” indicator LED comes in a variety of colors



Pin Configuration

The power module connects directly to your breadboard. Each side can be independently selected for 3.3V or 5V power via jumpers.

In the middle is a set of male headers for 3.3V, 5V, and ground.

Specifications

- Minimum input voltage: 6.5V (DC)
- Maximum input voltage: 12V (DC)
- Output voltage: 3.3/5V (selectable)
- Maximum output current: 700 mA
- Barrel jack plug size: 5.5mm x 2.1mm

555 Timer

Overview

The 555 timer is a collection of components that can be configured to provide timings and oscillations.

It uses two voltage levels—one-third supply voltage and two-thirds supply voltage. Internally, it consists of:

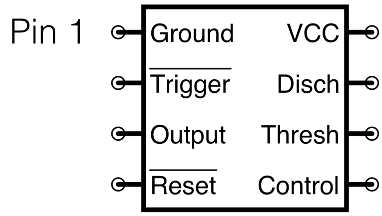
- Two comparators (one for each voltage level)
- A flip-flop (single bit storage) to know what state it is in and to switch states at the appropriate time
- An output driver
- A reset button

The timer relies on external circuitry (such as an RC time circuit) to supply timings.

The timer effectively has two states. In the “charging” state, when the **Discharge** pin is disconnected, and the **Threshold** pin is waiting for a high (2/3) voltage. In the “discharging” state, the **Discharge** pin is connected to ground, and the **Trigger** pin is waiting for a low (1/3) voltage. The typical usage is to provide an oscillating circuit.

Variations

- Can be implemented using CMOS/FETs or BJTs. FET implementation consumes less power, but can source less output
- Many variations in maximum oscillation frequency



Pin Configuration

- **Trigger** and **Threshold** detect going below 1/3 and above 2/3 voltage, respectively
- **Discharge** provides a ground that is only attached when the chip is in the discharging state.
- **Output** supplies a high voltage when the chip is in the charging state, and a low voltage when it is in the discharging state.
- **Reset** should be normally tied to a positive supply - it resets the circuit when it goes low.
- **Control** is normally connected to ground with a capacitor (10 μF recommended).

Specifications

- Supply Voltage: Usually 2V to 15V
- Output current: 100mA—200mA

Example Circuit