Herding Electrons

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Preface

Electronics has once again become a popular hobby. The current maker movement has brought a lot of people to electronics in recent years. It is a great hobby and can be very fun and rewarding. It can also be frustrating at times when needed information is hard to get.

There are usually two ways to learn electronics. The first is to attend a university and get a degree in electrical engineering or something similar. The second is to learn from books and online tutorials and web sites. The first method will give an in-depth understanding of the subject, but it will typically take four or more years and require a lot of heavy duty math and physics. That is the way to go if you plan a career in electronics, but it is rather extreme for a hobbyist. The second method is good for a hobbyist, but too often many of the details are either misunderstood or not learned at all. Often they are not covered to avoid the math or physics involved in a full explanation. Although that is fine for a hobbyist just starting out, eventually the lack of understanding will cause problems. Especially when projects become more advanced. Rules of thumb that hobbyists learn will work in most cases, but knowing when they won't and what to do about it are critical to success.

If a hobbyist realizes they are missing something and turn to books or web pages to fill in the gaps they will normally find it tough. The available material will either be intended for university students or practicing engineers and full of the math and physics they sought to avoid. Or the alternative is more of the hobby oriented material that leaves the details to the imagination.

This book is intended to fill in the gap. The idea is to cover all of the basic principals that hobbyists typically don't learn, but based on a practical explanation rather than a mathematical one. There will still be math involved, but the concepts will be explained with (hopefully!) simple English rather than equations. Most of the math used will be no more complicated than high school algebra and maybe a little trigonometry. And if you skip over or don't quite understand the math you should still be able to understand the concepts. I do reserve the right to throw in some more advanced math where appropriate. But again, skipping it shouldn't detract from your understanding. The concepts will be emphasized with hands-on experiments and projects.

No book can ever be a complete course on electronics. The field is just too big. We will try to cover all of the basics that most hobbyists will be interested in. With a solid understanding of the basics covered here, learning more advanced parts of the field should be straightforward. We will try to keep it interesting. Colored text boxes will be used to present additional information: red for important warnings, yellow for things to watch out for, green for historical or otherwise interesting material, and blue for experiments to try.

The book is intended for people interested in electronics but have no background at all. We will start with an explanation of what electricity is and how it works and advance from there. It is best to read from chapter 1 and go sequentially through the chapters. If you want to jump around then feel free, but please do go back and read earlier chapters at some time: you may find some good information that you need later.

I hope you enjoy this book and I hope you find electronics as fun and rewarding as I do.

Part I

Direct Current (DC)

Chapter 1

Basic Electricity

To understand electronics, we first have to understand electricity.

1.1 Introducing the Electron

Electrons are our friends. They do a lot for us, and don't ask much in return. Maybe you remember learning about atoms and protons and neutrons and electrons in school. Not to berate the protons and the neutrons any, but the electron is our favorite. The atom has a nucleus that has protons and probably some neutrons all packed in together. The proton has a positive charge and the neutron has no charge. Around the outside of the nucleus are the electrons, flying around in a cloud. Electrons have a negative charge.

Electrons are like little kids. They are full of energy! Always zipping around! They are also really small. If you drop one on the carpet it will be *really* hard to find. The classical picture of an atom looks like the picture below. It shows the nucleus in the center, with the electrons circling like little planets in orbit. We know now that isn't quite how it works. The electrons aren't really in any certain orbit. Instead, they are somewhere within a cloud, depending on how many electrons there are and how much energy the electron has.

Electronics is all about electrons. We need to get friendly with them so we know what makes them tick. We are after world domination. Or at least domination over electrons. We need them to do our bidding.

In the picture above we saw that electrons fly around the outside of the atom. When atoms are close together, like in a solid, it is common for an electron to move from one atom to the next. In a molecule, the electrons are shared between the atoms of the molecule. All this tells us that it isn't too hard to convince an electron to move away from its home atom. Little nomad particles, they are.

An atom is normally electrically balanced. It has the same number of negatively charged electrons as positively charged protons. But if we pursuede an electron to move away and it isn't immediately replaced, it will leave behind a "hole" that is positively charged. Holes will be important later on.

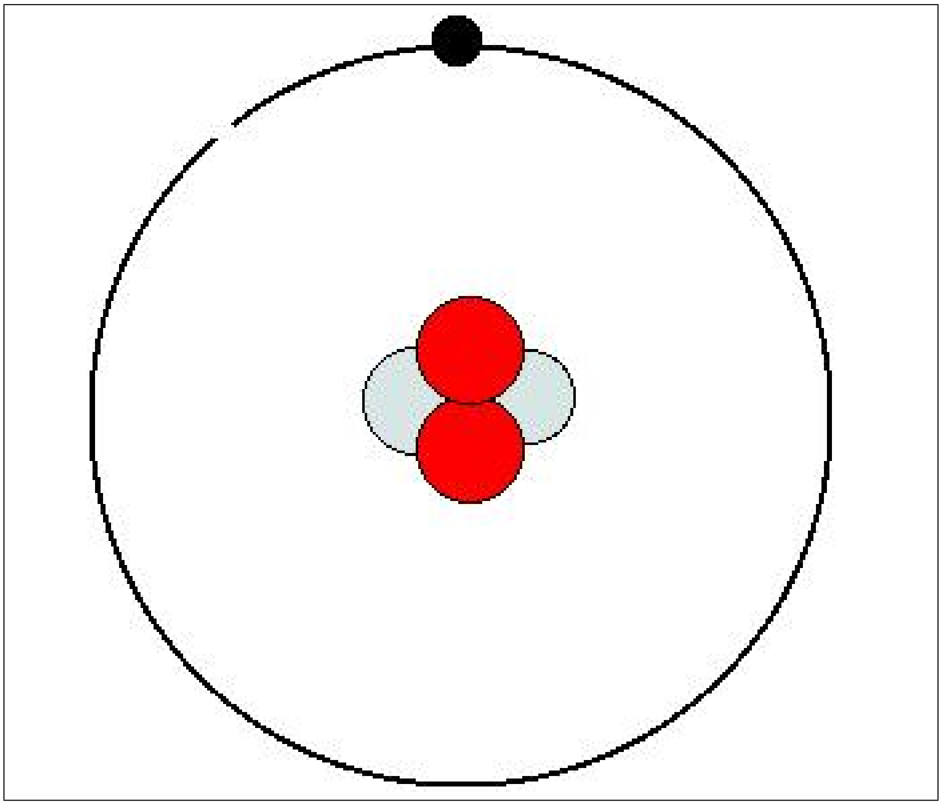

Figure 1.1: A simple atomic model

Ben Franklin and the Party Poopers

Benjamin Franklin, among many other attributes, was a scientist. He conducted many experiments with electricity. At the time, electricity was considered a fluid, and there were two types: resinous and vitreous. Franklin realized that the only difference between the two was the charge. So he labeled one “positive” and one “negative.” Later it was discovered that the negative charge was carried by the electron. By that time, current had been declared to flow from positive to negative. Once the electron was discovered, it was realized that electricity flow was often electron flow. Electrons travel from the negative to the positive. Most people didn’t take much notice. We call current flow from positive to negative “conventional current flow” and from negative to positive “electron current flow.” For most purposes it doesn’t really matter. The physicists, chemists, and electrical engineers just accepted it and kept on partying.

But then, around World War II, the US Navy started teaching a lot of people about electronics. For some reason, using government logic, it was decided to teach electron flow. Now, some seventy years later, there is still a small but very vocal group of these people. They insist that electron flow is the *one true way.* They show up in letters to the editor, comments in blogs, and at partys. They yell and scream that nothing is right unless we use electron flow. They are party poopers! Stay away from these people. They are trouble. They will tell you everything you know is wrong. They set out to confuse the non-believers. They cause cancer and global warming!

It is good to know how electricity flows, but it really doesn’t matter which direction you consider it to flow. All the scientists in the world have made peace with this seeming inconsistency. It is easier to just go with convention and say electricity flows from positive to negative: conventional current flow. Forget about electron flow. Don’t invite the party poopers to your next party!

Here’s some gossip about positive and negative charges: they like each other. If you get them together, they will pull toward one another with some force. At the same time, they don’t like their own kind: two positive or two negative charges will push away (repel) from each other. That property is extremely important. It keeps us from falling apart. It keeps us from falling through the floor to the center of the Earth. And it allows us to use these electrons (and protons!) to get some work done. So, we have these electrons that are just itching for a road trip. In a solid, such as a wire, they just kind of float around aimlessly. With a little bit of a push, we can get them moving in the direction we want. Then, we can get them to do some work for us. Let’s find out how.

1.2 Current

In certain types of materials, like most metals, there is a large number of electrons floating around aimlessly, like a fluid. For a moment, think of that electron fluid as water. A lake or pond is a body of water that is typically rather still. But if that flows into a stream, it moves. We call that moving fluid a current. For our electron fluid it is the same. When the electrons start moving in some general direction, we call it a current. We measure the current by counting how many electrons pass a certain point in one second. The units we measure in are called *amperes* or just *amps*. When about $6.241x10^{1}8$ electrons pass a point in one second, we call that one ampere. You don't need to remember that number, but you will see it again. Whenever electrons are moving they also create a magnetic field (even when just orbiting an atom!) We will see more about that later. I mention it now because there is another definition of an amp based on that magnetic field. If two wires each carrying one ampere are one meter apart, the magnetic fields will attract or repel with a force of $2x10^{-}7$ Newtons. That is actually the current definition of the ampere, but for our purposes the previous definition works better. When referring to current in equations we normally use the letter i or I.

Those facts may or may not be interesting to you, but the main points to get from all of that is that current is a count of how many electrons are passing a point in one second, and we measure it in amperes.

Andre Marie Ampere

The Ampere was named after Andre Marie Ampere, a French physicist and mathematician. Physicists are smart, but maybe not so creative: whenever they find something new, they tend to name it after one of their dead colleagues.

Ampere was one of the elite French intellectuals in the early 1800s. Although self-taught, he held several prestigious positions. His work with electricity and magnetism is what got his name attached to electric current. Much of the ground work of how we use electricity today was laid down by Ampere. His name is also one of seventy two that are inscribed on the Eiffel tower.

Electric current almost always has to come back to where it started. Again, take a look at water. The current in a river (flowing water molecules) flows into a larger river and eventually into the ocean. But if the ocean just kept filling up, eventually the river would run out of water and the ocean would be too full to accept any more. But that doesn't happen. The water evaporates from the ocean and forms clouds. Those clouds move over land and rain, which again provides water to the river. It's a cycle, or a circuit. Electronics is the same. All those electrons we push through a wire need a path to get back where they started.

Electrons carry energy that we use to do work. They don't really have useful energy of their own: we have to add it by pushing on them. We will see how to

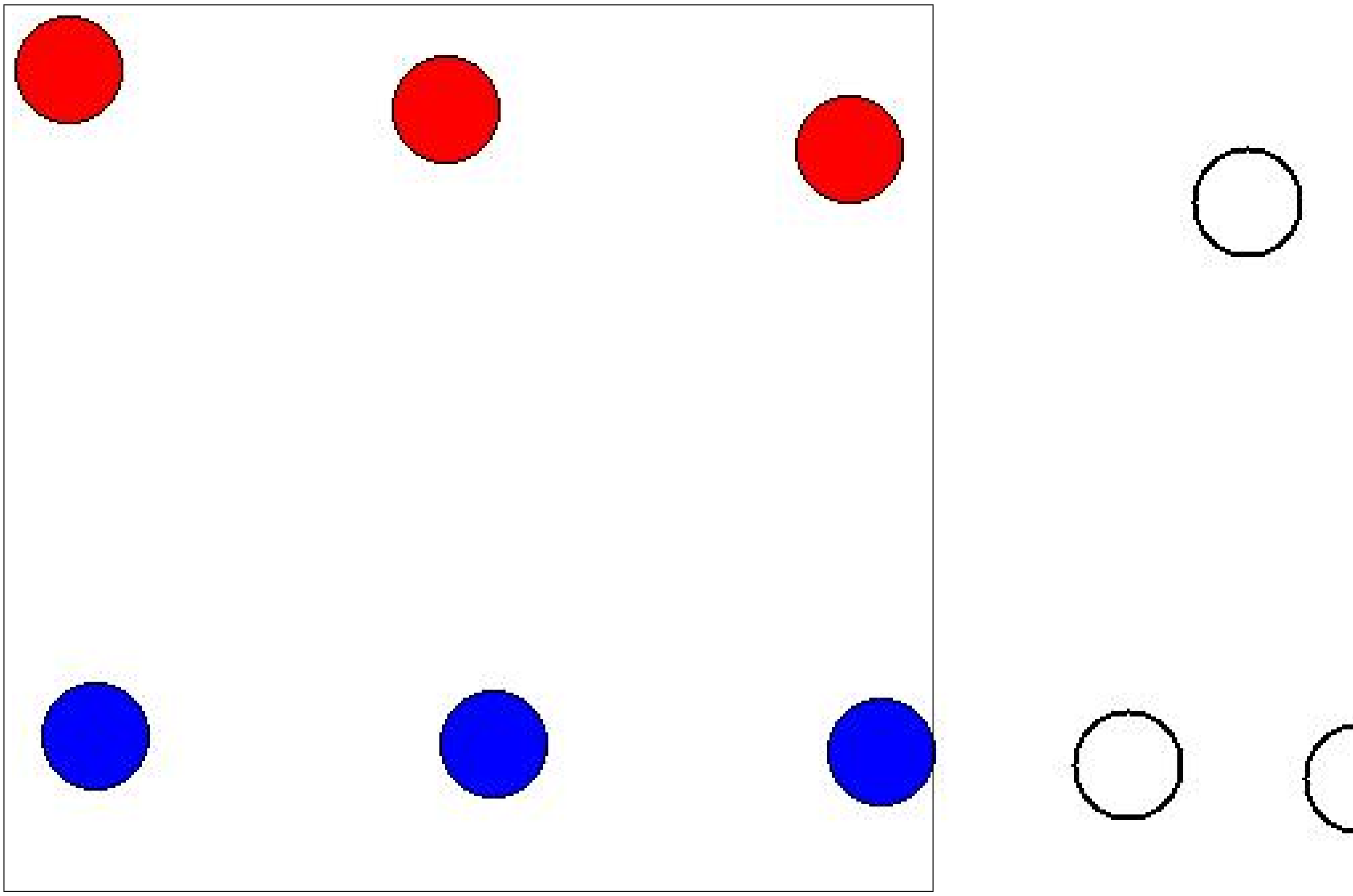

Figure 1.2: Electrons doing work

do that shortly. Let's take a look at a day in the life of an electron.

Little Papa Electron gets up in the morning. His wife hands him a lunch box full of energy and he heads off to work. He has to use some of that energy to get to work, but usually not much: the wire he travels on makes it pretty easy. When he gets there he works really hard to impress his boss and uses up most of the rest of his energy. He saves just enough to get home, and then heads out. Traveling back home he uses up everything he has left and arrives back home with no energy at all left. As soon as he gets there, his wife hands him another lunch box full of energy and he heads off to work again, repeating the cycle over and over. He doesn't stop until either the energy all runs out, or someone breaks the path he uses to get to and from work.

One thing to note about current that is very important: at any point along the path the current will be the same as at any other point. If the path divides into more than one path at some point (like a multi-lane highway) the sum of currents in all those *parallel* paths will be the same as at some other, single

Figure 1.3: Equal current

lane, path.

1.3 Voltage

We have mentioned a few times that we need to push the electrons to get a current flowing. How do we do that? They are pretty small, so it's kind of hard to put your hand on one and push it along. Maybe we can use their own properties to do it? There are a few ways to do that. Remember that we mentioned electrons will repel each other? If we cram a bunch of electrons together they will push away from each other, trying to get as far apart as they can. If there is an escape path, say a wire, they will flow along that path and equalize the distance and repelling force on themselves. How can we cram a bunch of electrons together to make that happen? One way is a chemical reaction that releases electrons. That is how a battery works. A chemical reaction inside the battery releases electrons at one terminal (the negative terminal). Those *extra* electrons repel each other and cause a current to flow if there is a path. The electrons will flow through the circuit and return in the positive terminal.

Another way to push the electrons is with a changing magnetic field. Earlier we said that any time an electron is moving it creates a magnetic field. Electricity and magnetism are very closely related. It turns out that electrons will respond to a magnetic field as well. Electric generators, as well as many instruments, take advantage of this. When you plug a device into a mains outlet, that electricity is almost certainly generated by spinning wires and magnets in relation to one another. There will be a lot more to say about that later.

Experiment: Generating Electricity

Let's try our first experiment. We will generate a little bit of electricity and create a current flow to light an LED (Light Emitting Diode.)

Another way we often power projects is with a *solar cell* or *solar panel*, more accurately referred to as a *photoelectric cell.* We will mostly use the term solar cell here. A solar cell takes light energy and converts it to electric energy. It is interesting that the *photoelectric effect,* which is what the solar cell uses to convert the energy, is what Albert Einstein won a nobel prize for. He did not win one for relativity! Einstein's explanation of the photoelectric effect was the first real shot that led to quantum physics. Basically, when a photon (light particle) strikes an atom, it adds just enough energy to an electron to knock it loose and cause it to flow as current. But anyway, a solar cell will absorb light and generate electricity from it. Solar cells are often ideal for low power circuits that will have light available and for projects that can't depend entirely on batteries or other power sources.

No matter how we create the force that pushes electrons along and causes current to flow, it is called *electromotive force* (abbreviated *emf*)and is measured in *volts.* In physics and electrical engineering electromotive force is the standard name. Most of us, however, use the word *voltage* in daily use. For most of our purposes, the two are interchangeable. The letter "V" is used for voltage, but often you will also see "E." In this book we will mostly use "E" but you might see a "V" show up once in a while. Get used to it. You will encounter the same thing as you read books and web pages. It's good to be used to using both from the start.

Allesandro Volta

In another brillian flash of creativity, physicists named the volt after another dead physicist: Allesandro Volta.
Volta created the *voltaic pile* in 1799. The voltaic pile was the first battery and was created from zinc and copper disks separated by cardboard or felts spacers soaked in salt water. Before this invention it was widely believed that electricity could not be generated by chemical means.

In hobby electronics projects the electromotive force, or voltage, is typically provided by a *battery.* The term battery is quite often misused, as I am doing now. What we should say is that the electricity is provided by an *electrochemical cell* or a *battery of electrochemical cells.* A battery means there are more than one. As an example, a standard "AA" battery is actually a single cell but a "9 volt" smoke detector battery is actually a battery since it contains 6 cells.

1.4 Resistance

If you turn on the water in a water hose, water will come out the end at some rate of flow. If you then squeeze or crimp the hose, that rate will become less. The hose *resists* the flow of the water. Changing the size of the hose changes the amount it resists. This resistance limits the amount of water that flows through the hose.

If you leave the hose alone and then adjust the faucet to provide more or less pressure, the amount of flow will again change, higher or lower. So, it seems that the flow rate, or current, depends on the pressure and the amount of resistance in the hose.

The same thing happens in electricity. Any *conductor* that can carry a current will have some amount of resistance to that flow. The amount of resistance determines whether it is a good conductor, or a poor conductor (called an *insulator*.) We call this *electrical resistance* or simply resistance. Electrical resistance is measured in *ohms* and is represented by the letter R or r. Instead of writing out the word ohms, we normally use the capital Greek letter Omega (Ω).

Georg Ohm

When electricity flows through a resistance, energy is used up. One thing to always keep in mind is *conservation of energy.* Energy is never created or destroyed: it only changes form. In this case it is converted from electrical energy to heat energy. A resistance with current flowing through it will give off heat.

Conservation of Energy

The above two notes are very important and both are often overlooked by people new to electronics. I will mention them many more times in this book, but try to remember them now. The sooner the better.

Resistance is important in electronics. Since it limits the flow of current it is very useful. Special electronic components that provide resistance to be added to a circuit are the most common electronic component. They are called *resistors* and are used in almost every electronic circuit. They come in a wide variety of shapes, sizes, and values.

Superconductors

Another important note to keep in mind: *every* element that has current flowing through it has resistance! Some things have more resistance than others, and in many cases it is small enough to be ignored. But not always. Often, we have to consider the resistance of parts, say a wire, that we would normally think of as not having resistance.

1.5 Exercises

Chapter 2

Ohm's Law

So far we have learned the basics of electricity. Flowing electricity is called current, much like flowing water in a stream. The pressure, or force, that pushes that current is called electromotive force, or more commonly for us, voltage. And just like everything else in the world, the current will meet with resistance to its flow. Now it is time to see how these three basic items fit and work together.

2.1 Relationships

Voltage, current, and resistance are closely related. We saw in the previous chapter that voltage is just a force pushing on the electrons. It may be generated from a chemical reaction, or from light striking a solar cell, or from an electrical generator. No matter what the source of voltage, it is just a way of converting one type of energy (chemical, light, or mechanical) to electrical energy. Voltage tried to push the electrons away. If there is a path for them to follow and get back to their starting point, they will flow along that path and create a circuit. The current flow is caused by the voltage. But along the circuit the current will meet resistance and that resistance will limit the amount of current that flows. It's important to remember that no current flows if there is not a complete path, or circuit.

In the early days of electricity the full relationship between these three elements wasn't clear. Georg Ohm found and stated the relationship that now bears his name.

2.2 Don't Break the Law

Georg Ohm

2.3 Exercises

Chapter 3

DC Circuits

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3.2 The First Circuit

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Part II

Alternating Current (AC)

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