Chapter 3

Electricity

Chapter Objectives:

1. Define key terms: charge, electron, proton, neutron, current, conducting path, resistance, electric potential, magnetism, and circuit

2. Describe the interaction between charged particles. Be able to use the equation for the electrostatic force.

3. Define resistance and resistivity. Understand and be able to use the equation that relates the two.

4. Describe why houses are wired in parallel and not in series.

5. Define Ohm's Law and be able to use it in word problems.

6. Describe Faraday's Law of Electromagnetic Induction and how it can be used to run a generator.

7. Mathematically describe and be able to use the relationship between power, current, and voltage for an electrical current.

8. Mathematically describe and be able to use the equation for the power lost in a resistor.

9. Describe why alternating current is used in the U.S. to transmit electricity.

Introduction

In the previous chapters, we have discussed the basics of energy: what it is, how it is transferred, and rules regarding those transfers. Our discussion has been fairly non-specific in regards to what types of energy are to be considered. In this chapter, we will focus on electricity, and for good reasons: the largest sector for our energy usage is electricity. Over 1/3 of all of the energy consumed in the U.S. goes toward the creation of electricity. Electricity runs almost every appliance in our homes, from computers and stereos to refrigerators and air conditioners. As we begin to move to electric cars which are more efficient and becoming increasingly more available, we can be guaranteed that the generation of electricity will have to increase to sustain our lifestyle.

Most of the electricity in the U.S. is created at centralized facilities that service a large region. This electricity is generated mostly from the kinetic energy of a turbine that is being driven by fossil fuels being burned, with less than 30% of it being generated from nuclear or renewable energy sources. After creation, it is sent to homes and businesses over an amazing grid of wires that span hundreds of miles. There, some of the appliances use the electricity to generate heat, while others use it to record/process signals or to convert it back to kinetic energy of spinning axles. In order to understand how this all takes place, we need to review a little bit of the subject of electricity and magnetism.

Charge: All About the Benjamin

Benjamin Franklin is one of the most famous American statesmen. He is hailed throughout most history classrooms in the U.S. as one of the leading Founding Fathers and a great politician. As a sidelight, historians will tell tales of his “other” adventures as a journalist and inventor. In particular, they show images of him flying kites in a storm with a key attached to it to attract lightning and maybe tell tales of a few of his inventions

What rarely, if ever, gets told is that one of the reasons why Benjamin Franklin was able to be a great statesman was because of his fame and renown as a scientist. It is not that Franklin was an inventor that “dabbled” in science; he was one of the foremost scientists of his time. He did pioneering work on the discovery of the Gulf Stream in the Atlantic Ocean. He recognized internal waves on the water/oil interface in Italian lamps. Most importantly, he developed the entire notion of all neutral matter being composed of particles of opposite charge in equal numbers.

Fig. 1: Benjamin Franklin

Since the earliest of time, humans had played with static electricity. It was well known that rubbing a piece of amber with fur allowed one to pick up tiny bits of dried leaves with the amber. Later cultures found that the same sort of thing could be done with rubber and fur or silk and glass. However, in the thousands of years in which this knowledge existed, no one was able to accurately describe what was going one to cause the attraction. It was Franklin who developed the idea of charged particles that attracted one another and the notation of positive and negative charges.

The development of this idea alone would be enough to secure any scientist worldwide recognition. Franklin built upon this idea to discover that air was much more likely to breakdown in the presence of a sharp charged conductor, and hence, the development of the lightning rod design that we still use today. For all of his work in science, he was made the only foreign member of the French Academy of Science, which was the premier science organization of its time. This honor is one of the reasons why Franklin was called upon to be the ambassador to France from 1776 to 1785. The French had great respect for him, and aided the cause of the U.S. during this time by sending aid and troops in our war with England.

Franklin's discovery that all neutral matter is comprised of charged particles was a tremendous step forward in our understanding of the atom. His model was quite simple. Although he knew nothing about the atomic structure that we know today (Fig. 2), he theorized that matter was made of negative particles called **electrons** and positive particles called **protons**. When an object like glass is rubbed with silk, some of the negative matter is rubbed from the glass and deposited on the silk. This makes the glass have a net positive charge and the silk to have a net negative charge. Franklin's theory held that like charges repel, while unlike charges attract. This meant that the glass and the silk would be attracted to one another, and if allowed to touch, the charge would redistribute itself such that both items no longer had any net charge.

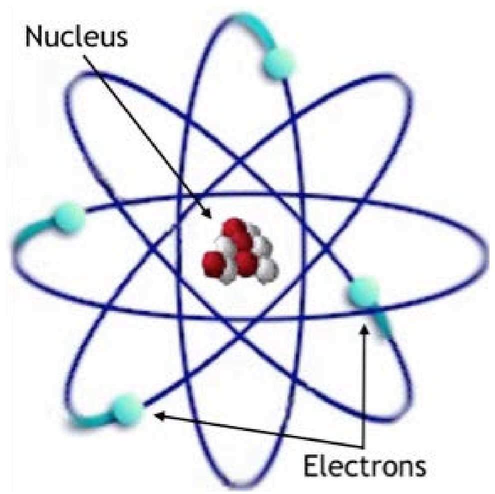


Fig. 2: model of an atom

Our understanding of matter today is based upon this early theory of Franklin's. At energy levels found in our everyday life, matter is made up of three different particles, which have three different charges. **Neutrons**, which normally exist in the nucleus of the atom, are neutrally charged and have a mass of 1 atomic mass unit (1 amu = 1.6×10^{-27} kg). Protons, which also normally exist in the nucleus of the atom, are positively charged and have a mass of 1 amu. The last particle is an electron, which is negatively charged, exists outside of the nucleus, and is rather light (about .001 amu). The size of the charge on a proton or electron is 1.67×10^{-19} C, where C stands for coulombs, which is the basic unit of charge.

The force between the particles is called the **electrostatic force**. As we saw in Chapter One, it depends upon the size of the charges involved and the distance between them. In particular, the force is given by the equation

(Equn. 3.1)

$$F = Kq_1q_2/r^2$$

where $\mathbf{q_1}$ and $\mathbf{q_2}$ are the size of the charges on the particles in units of coulombs, **K** is a universal constant equal to 9×10^9 N m^2/C^2, and **r** is the distance between the centers of the particles. Much like with gravity, this formula shows that the further that the particles are removed from one another, the smaller the force between them becomes. If you double the distance between the two, the force between them drops by a factor of 4. Conversely, if you cut the distance in half, the force quadruples.

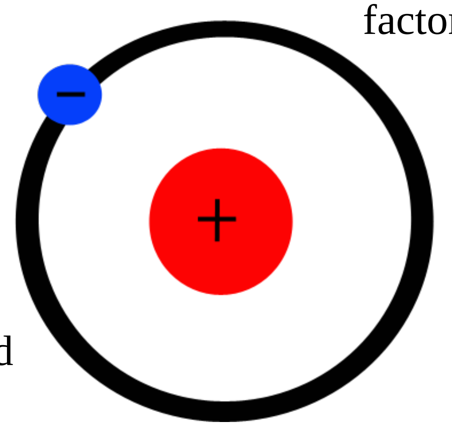


Fig. 3: neutral hydrogen atom

As an example, let's look at the force between the proton and the electron in a neutral hydrogen atom. The charges on the particles are as listed above, and the average distance between the two particles is about $.53 \times 10^{-10}$ m. Plugging into the formula, this gives a force of

$$F = (9 \times 10^{9}\ Nm^2/C^2)(1.67x10^{-19}\ C)(-1.67x10^{-19}\ C)/(.53 \times 10^{-10}\ m)^2$$

$$F = -\ 8.9 \times 10^{-8}\ N$$

The negative sign here denotes that the force is attractive. While the size of this force is quite small, the fact that it is operating on such small particles of 1 amu or less means that the acceleration can be quite large.

Nuclear Forces

Before we leave the atom and start discussing moving charges, a small aside is in order to lay the groundwork for Chapter Eight. If you are like most students who have gone through the American K-12 educational system, the foregoing discussion of charges has probably been introduced multiple times in your science classes. You have had it drummed into your heads that unlike charges attract and like charges repel. You might have even had someone say that this is what holds the atom together, the attraction between the protons and the electrons.

If so, what you probably did not hear about is what holds the nucleus together. Think about it: neutrons have no charge while the protons are all positively charged. For an atom like helium, the nucleus has two protons, which should be repelling each other with a great deal of force, and two neutrons, which should not be attracted at all to each other or the protons. Using only electrostatic forces, there is no way that the nucleus should exist, as it would fly apart.

In order to keep all of the neutrons and protons together in the nucleus, other forces are required. The two that act to do this are the weak and the strong nuclear forces. While the description of these two forces is exceedingly complicated, one can understand a little bit about them on a basic level. As one might guess, the weak force is not very strong and has a limited range of distance over which it operates. One can say that it aids in holding the neutron and proton together, as it is the force that is involved in the decay of either of these **nucleons** when the there is a beta decay. Likewise, the strong nuclear force is very strong (100 times stronger than the electromagnetic force), although it, too, is limited in the range over which it operates. The strong force is responsible for holding the protons and neutrons together in the nucleus.

Current

We will come back to the nuclear forces in Chapter Eight when we talk about radioactivity and nuclear reactors. For now, let us get back to charged particles. The fact that there are forces between charged particles means that we can use them to transfer energy if we allow the charged particles to move under the influence of these forces (Remember: work is a force acting through a distance). Thus, in order to study electrical energy, we need to investigate the movement of charged particles and factors that affect this. This movement is defined as a **current**, which is an amount of charge that passes a particular location per unit time. As a formula, we would write this as

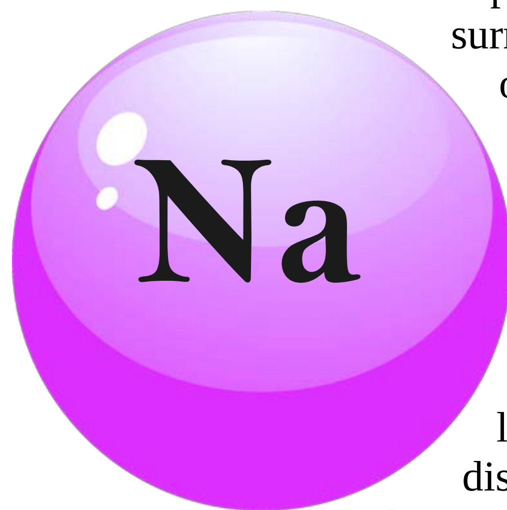
(Equn. 3.2)

Current = I = (amount of charge past a point)/ (elapsed time)

In the SI system of units, current is measured in **amperes** (A), which is equal to 1 C/sec.

The first issue in regards to current is what type of charged particle would be used in such a flow. Both electrons and protons reside in atoms (see Fig. 1) and are not necessarily free to move outside of it. The proton, with its mass ($m_p = 1.7 \times 10^{-27}$ kg) being a thousand times larger than that of the electron (me = 9.1×10^{-31} kg), would be much harder to accelerate. However, acceleration is not the only consideration. In order to move a charged particle freely, it must be liberated from the atom first. Removing a proton from the nucleus is very hard, as the strong nuclear force is 100 times stronger than the electrostatic force when operating over the short distances found in the nucleus (never mind the fact that removing a proton from the nucleus would actually change what type of atom it was). Electrons are much easier to remove in certain atoms because the configuration of electrons shields some electrons from the full strength of the nucleus. While all of the electrons are attracted to the nucleus, all of the electrons are repelling each other as they move around in the atom. If sufficient numbers of electrons are bunched near the nucleus, then their repulsive force screens the full impact of the nucleus from outer electrons and makes it easier to free them from the atom.

As an example, let us look at a sodium atom. A neutral sodium atom consists of 11 protons in the nucleus that are



surrounded by 11 electrons (the number of neutrons can vary, but the number is irrelevant for this discussion). Because of rules that we will not go into here (see the **Pauli Exclusion Principle** if you want to understand further), the electrons pair up within the atom in different manners that leave them, on average, at different distances from the nucleus. Ten of the electrons spend the vast majority of their time closer to the nucleus than the eleventh one, leaving it further away. The screening of these ten electrons means that the eleventh electron has, on average a smaller force on it toward the center of the atom and makes it much more likely to be liberated from the atom when other forces outside of the atom come into play. This ability to readily lose an electron is not true of all atoms, but is true of a subset of atoms known as **metals**, which are defined by their ability to give up electrons.

In order to transfer energy with electricity, we are going to need a source of electrons that can both create free electrons and provide the electromotive force to propel them. This, alone, is not sufficient for there to be a current, or stream of electrons. In order for these electrons to flow from the source, they will need a conducting path over which to flow. Without such a path, the electrons will just pile up around the source, much like cars in a parking lot with no road to travel on. As you can probably guess, these paths normally will be made out of metals, as they have enough electrons that are free that they can carry currents very readily.

Potential Differences

Let us first investigate the application of a force on the electrons that can give them kinetic energy. As electrons respond to electrostatic forces, one way to force an electron would be to produce an **electric field** in the vicinity of it. This field will act much like we a gravitational field does to accelerate objects with mass. Because a charge particle entering this field would have work done on it by allowing it to move, an electron in the electric field has electrical potential energy (again, this is analogous to the gravitational potential energy that a particle with mass has near Earth). This potential energy for a constant electric field is given by

(Equn. 3.3)

$$\text{electric potential energy} = q\ E\ d$$

where **q** is the charge on the particle, **E** is the electric field, and **d** is the distance through which the particle will be allowed to move through the field. This looks very familiar to the gravitational potential energy (GPE = mgh, Equn. 1.9) for a particle with mass near a constant gravitational field.

Because the electric field is a vector quantity and can be complicated, we normally just talk about the **electric potential**.

This quantity is a product of the constant electric field and the distance over which it operates, V = E x d (for a non-constant electric field, it can be calculated by integrating the electric field over the distance). You are probably very familiar with this term, as electric potentials are expressed in units of volts. As an example, the outlets in your home operate at a maximum of 110 volts, with the exception of the high voltage outlets for dryers, air conditioners, and ovens, which operate at a maximum of 220 volts.

This potential can be created by a variety of methods. Some of these will be discussed later in the chapter (generators) while others will be discussed in later chapters (photovoltaic cells).

The one we will discuss here is the first one created commercially: a **battery**. Most people are familiar with the use of a battery, although they might not be familiar with the workings of one. A battery consists of two half-cell reactions within which two dissimilar metals interact in an acid or base solution. When the metals are placed in the solution, reactions will take place, leaving one with an electrode (the metal) and a solution containing electrolytes. Because the two metals have different reaction energies with the acid or base, one of them will have a greater preference for taking electrons from the solution. This metal will become the negative electrode or anode, while the other will become more positive (cathode).

When the two electrodes are connected by a conducting path, the negative ions in the solution will move to the anode while the positive ions move toward the cathode. The negative ions will react and give up electrons to the anode. These electrons will be attracted through the conducting path to the cathode. Upon reaching the cathode, the electrons react with the positive ions, thus completing the circuit. Figure 4 shows a diagram of such a battery cell.

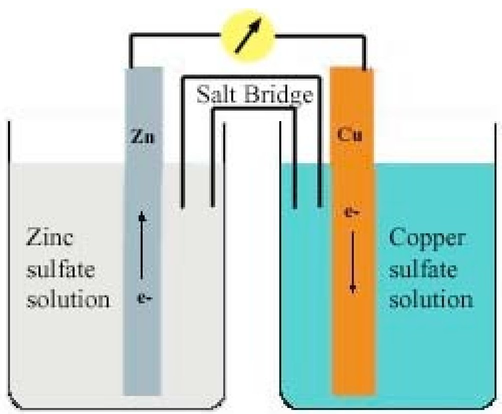


Fig. 4: galvanic cell

The amount of electric potential from a battery depends upon the individual potentials of the metals and the electrolytes. For example, in Figure 4, we have copper and zinc in our galvanic cells. The potential for Zn to go into solution as Zn^{+2} and liberate 2 electrons is -.762 Volts, while the potential for Cu to go into solution as Cu^{+2} and liberate 2 electrons is -.360 Volts. Since the zinc reaction is more electronegative, it will be the anode while the copper will be the cathode. This means that the cathode reaction will be 2 electrons combining with a Cu^{+2} ion to create Cu at a potential of .360 V. The differences in potential between these two reactions is .360 V - (-.762 V) = 1.10 V.

It should be noted that a battery does not necessarily require a wet solution, as there are dry cell batteries that carry out these same chemical reactions with a paste around the electrodes. Whether it is a wet or a dry cell battery, the key characteristic of these devices is their portability, which means that the cells need to be enclosed. Our modern way of life depends on this portability, from the 12 V battery in our cars to the small batteries in our cell phones and laptops.

While they are a potential source, batteries are really just storage devices for energy generated by other methods. The chemical energy that they have is created by passing currents through solutions reverse the chemical reactions above. The currents used for this are created by other means. Portability is great for our modern lifestyle, but without these other sources of electrical energy, that portability would not be possible. For now, we will leave this discussion of generating electrons in order to discuss how to move these electrons to where they are needed.

Conducting Paths

Because metals can so readily lose an electron, they not only form the basis of most sources of electrons, but also of the **conducting paths** that the electrons will follow as energy is transferred. The reason for this is simple. If we could build pathways that were complete vacuums, then the electrons could be transmitted quite freely by just putting them in the vacuum and applying electrostatic forces to propel them. However, in the real world, any pathway that we make is going to be comprised of atoms, as maintaining vacuums it incredibly expensive and non-practical. If these atoms are the kinds that do not give up outer electrons very well, then the electrons we try to send down the path are likely to hit the atoms and become stuck by the attraction of the protons in the nucleus. Therefore, we need a pathway that is comprised of atoms that do not take in electrons without readily giving them up; hence, most conducting paths for electricity are comprised of metals like copper, gold, silver, or aluminum.

Not all metals conduct electricity as well as others. For instance, gold is a better conductor than aluminum, although you rarely find gold wires in anything but very specialized situations. For many years, we have used copper, which is still better than aluminum, but the cost of this has gotten so high that we are beginning to only use it in special situations. A measure of how well a material carries current is given by its **resistivity**. The better a substance conducts electricity, the lower the resistivity will be. Most good conductors like silver, copper, and aluminum have resistivity values on the order of 10^{-8} ohm meters (see table), while poorer, non-metal conductors like silicon (.1 ohm meters), and glass (10^9 ohm meters) have much higher values.

MATERIALS	RESISTIVITY [Ω•M] AT 20 °C
SILVER	1.59×10^{-8}
COPPER	1.68×10^{-8}
GOLD	2.44×10^{-8}
ALUMINUM	2.82×10^{-8}
IRON	1.0×10^{-7}
CARBON (AMORPHOUS)	5.0×10^{-4}
SEAWATER	2.0×10^{1}
HARD RUBBER	$\sim 10^{13}$
QUARTZ (FUSED)	7.5×10^{17}

The resistivity of a wire saps energy from the flow of electrons. As an analogy, resistance tends to operate like friction does for moving macroscopic items. In essence, the atoms of a wire get in the way of the electrons flowing through the wire; the higher the resistivity, the more they get in the way. When building wires, we normally want the lowest resistivity for a wire we can get in order to prevent energy from being lost, although the cost of the wire (again, not many gold wires out there, and increasingly, fewer copper wires) does enter into the equation. The only time that we do want high resistivity wires is when we want to transfer the electrical energy into heat, such as in the heating element on an electric stove top or heater. For those applications, fused quartz is an ideal substance.

The resistivities of substances exhibit temperature dependences, with values usually decreasing as the temperature of the substance is lowered. This is somewhat understandable using our very simplistic model of atoms in the wire getting in the way of the electrons flowing in a wire. As the temperature increases in the wire, the atoms vibrate more than they do when they are colder. This greater vibration means that the atoms effectively take up more space, which means they get in the way of the electrons more. As they cool off, they vibrate less and take up less room, lowering the resistivity.

For a small class of materials, there are temperatures at which the resistivity goes to zero. At these temperatures, these devices are **superconductors**, which means that they will not transfer any of the electrical energy to heat as a current flows through them. How they do this is beyond the scope of this book, but it involves quantum mechanical effects that effectively allow the electrons to pass around the atoms without any interaction. Creating materials that are superconductors at room temperature is the ultimate goal for some condensed matter researchers, as electric lines currently lose about 10% of all of their energy to resistance losses. With room temperature superconductors, we would be able to save this energy, which would greatly reduce the consumption worldwide.

The resistivity is not the only factor that affects the total amount of energy lost in a wire. The length of the wire also has an effect, as the greater length corresponds to a greater chance of encountering atoms that will impede the flow. The width of the wire also affects the amount of energy loss, as the narrower the path, the more interactions occur between the individual electrons and the greater chance of hitting an atom. Because there are other factors that affect the flow, we need to have another term that measures the total amount of impedance to the flow. This term, the **resistance** of a wire, involves the resistivity and the dimensions of the wire. In particular, the resistance is given by the formula

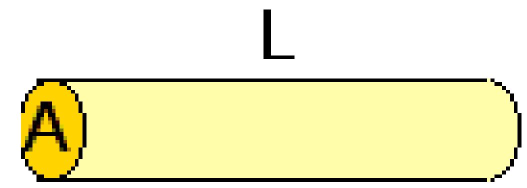


Fig. 5: wire diagram

(Equn. 3.4)

$$R = \rho L/A$$

where ρ is the resistivity, **L** is the length of the wire, and A is the cross sectional area of the wire (see Figure 5). The unit for resistance is ohms (Ω) in the SI system. (Video EXAMPLE)

As this equation shows, the resistance has a linear dependence in the length of the wire. Thus, if you make a wire twice as long, you will get twice the resistance. Around your house, this is usually not a problem, although connecting multiple, cheap extension cords can create problems. It is a huge problem, though, for electric companies that have to send electricity over long distances from the power plants to all of the homes in their market. As the distance between these two gets longer, the amount of energy lost becomes greater. This is a big problem in the Central and Western U.S., where people are spread out over a long distance.

This equation is also inversely proportional to the cross sectional area of the wire. This means that it is inversely proportional to the square of the radius ($A = \pi r^2$) if the wire is round. The thickness of a wire can make a huge difference in the overall resistance of a wire, which determines how much current the wire can carry safely. For example, the cheap six-foot extension cords that you can buy at any store usually use 18 gauge or hire wire (oddly enough, the higher the gauge wire, the thinner it is). This means that the diameter of the wire is less than 1.0 mm. These wires should never carry more than 5-7 amps of current. A good 50 foot or longer extension cord will use 14 gauge or lower wire, which corresponds to wires that are 2.5 mm or greater. Even though they are longer, these cords can carry over 15 amps of current through them safely. If more people understood this, there would be fewer people killed each winter. Invariably, someone will use one of these cheap six-foot extension cords to plug in a space heater that requires 10 amps or more of current. The result is that so much energy is lost by the high resistance in the cord that it gets hot enough to start a fire. Please, never make this mistake, as it can cost you your life or the lives of your loved ones.

Ohm's Law

Now that we have a source of electrons and a conducting path, we are ready to transmit energy with electricity. If we attach some appliance to a source with wires, the electrons will flow from the negative terminal of the source to the appliance and then back to the positive terminal of the source, thus completing the circuit. If the wire and the appliance have a total resistance R, then the amount of current I that will flow through the circuit due to the potential difference V is normally given by

(Equn. 3.5)

$$I = V/R$$

This relationship was found by the German physicist Georg Ohm in 1827 experimentally, and it holds true for most simple devices that we will consider. It does not hold true for objects that are non-ohmic, such as transistors, diodes, and other semi-conductors. For this course, we will not consider such devices in any calculations.

Fig. 6: Georg Ohm

As an example, let us consider an incandescent bulb with a tungsten filament. Before this bulb is plugged in, the resistance is typically small (about 10 Ω). As current passes through it, the filament becomes hot and increases in resistance. At operating temperatures of several thousand degrees, the resistance is about 150 Ω. If such a bulb is plugged into a 110 Volt peak source, then the maximum current flowing through filament is

$$I = 110\ V / 150\ \Omega = .73\ A$$

While not huge, this is still a substantial amount of current. (Video EXAMPLE)

Complicated Circuits

If all that we ever wanted to do is to run one appliance, then analyzing electrical circuits would be simple. However, our modern lifestyle calls for running multiple appliances at the same time, such as when we turn on a light while watching television. The addition of a second appliance requires that we make a choice in how to wire things. One way to wire the circuit would be to run two wires from the negative terminal of the source to each appliance and then run a wire from each appliance back to the positive terminal of the source. This is known as a parallel circuit since both appliances are directly plugged into the source. A second way to connect them is to run a wire from the negative terminal of the source to the first appliance, then from the first to the second, and finally from the second appliance back to the positive terminal of the source. This is known as a series circuit since the appliances are in a serial arrangement with the current flowing from one to the other.

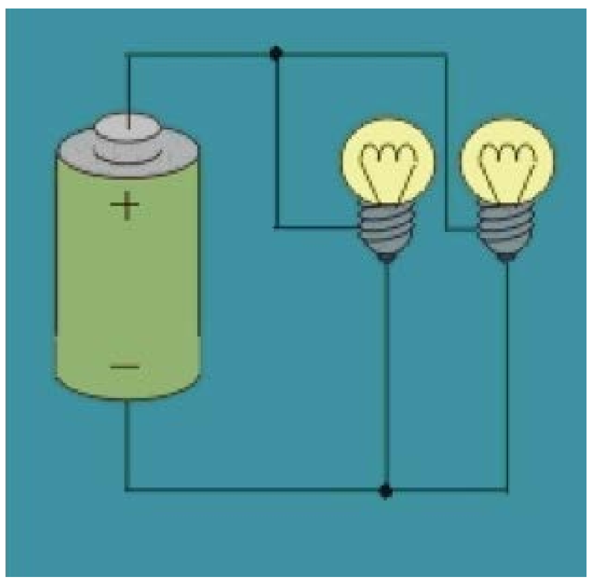


Fig. 7: parallel circuit

These two arrangements can require vastly different currents to power the circuit. Figure 7 shows a parallel circuit. In this configuration, each appliance is wired directly into the source. The amount of current that will flow through each one is just that given by Ohm's law. Thus, the total current being supplied by the source is (Video EXAMPLE)

$$I = V/R_1 + V/R_2 = V(1/R_1 + 1/R2)$$

This circuit has an effective total resistance that is given by

$$1/R_{total} = 1/R_1 + 1/R_2$$

If we go back to our example of a tungsten filament light bulb, we get

$$1/R_{total} = 1/150\ \Omega + 1/150\ \Omega = 2/150\ \Omega = 1/75\ \Omega$$

This means that the total resistance of the circuit is $R_{total} = 75\ \Omega$, which is less than either of the two appliances. Unlike the series circuit that had additional appliances increasing the total resistance, a parallel circuit effectively decreases the total resistance as you add more appliances. This makes a lot of sense, as each additional appliance gives the electrons a different path to take, which is the same as increasing the diameter of the wire.

This does present a problem if you wire in parallel. If too many appliances are added to the circuit, the amount of current that must be supplied by the source can get quite large. If it gets too large, the resistance in the main line that is supplying the entire circuit will cause the wire to get so hot that it will either melt or cause a fire. This is why all electrical circuits in buildings will have either a circuit breaker or a fuse in the main line. These devices are rated for different currents depending upon how thick the main wire is. If the current gets too large and gets near the maximum current that the wire can handle, either of these devices will be activated (the circuit breaker will flip open; the fuse will melt and break the circuit) and stop current from flowing. In the case of a circuit breaker, you need to unplug devices and go reset the breaker. In the case of the fuse, you need to unplug devices and go replace the fuse. If you do not have a fuse on hand, go to the store and buy one. You should never replace a burnt fuse with a piece of wire or a penny. That means that the circuit has no safety and can result in a fire starting in the wall if the current should get too large.

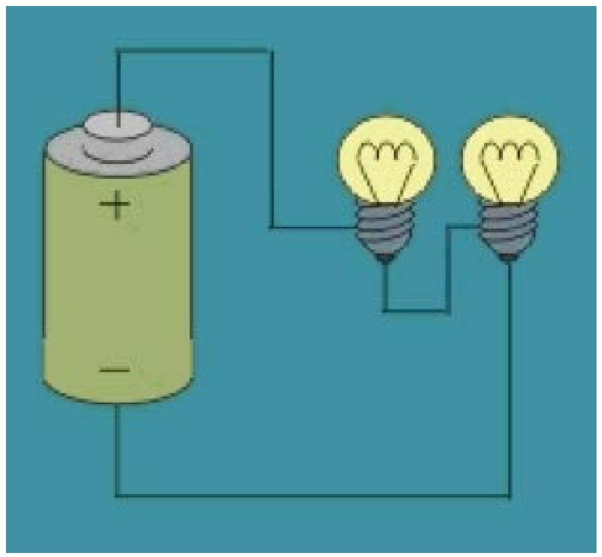


Fig. 8: series circuit

Figure 8 shows a simple series circuit of two light bulbs. We can consider the filament from one bulb to be put up next to that of the next bulb. If so, this means that the resistances of the bulbs will add together. If we consider R_1 to be the resistance of the first bulb and R_2 to be that of the second, then the total resistance is $R_1 + R_2$. This means that the current going through the circuit will be

$I = V/R_{total} = V/(R_1 + R_2)$ (Video EXAMPLE)

This shows that adding the second appliance increased the overall resistance, which decreases the total current flowing through the circuit. If we were to add additional appliances to this circuit, we would further reduce the current. Eventually, we could reduce the current so much that none of the appliances operated correctly. Clearly, this is not a way to wire one's house.

Current Conventions and AC/DC

So far, we have only discussed the current in terms of electrons flowing in one direction from a negative terminal to a positive terminal. While this is what happens in a wire, by convention, we take a current to be positive in the opposite direction of the electron flow. That is, we talk about a current flowing from the positive terminal of a source to the negative terminal of a source. We do this so that the math works out, as electrons have negative charges. There is nothing inherently wrong with this, as the convention of positive or negative signs is arbitrary. Ben Franklin would have done us all a huge favor almost three hundred years ago if he had chosen the electron to have a positive charge. Alas, he did not, which means that we have to talk about positive current flow in the opposite direction of the electrons traveling.

We also need to point out that electrons do not have to only flow in one direction. If they do, this is what is known as a **direct**

current or DC. Common sources of such currents are batteries and photovoltaic panels. However, current can change direction periodically. If the current alternates between flowing in one direction and then in another, this is what is known an **alternating current or AC**. Common sources of these currents are generators. Both types of currents have their pros and cons. DC can be much more efficient in motors, but AC can be much more efficient on transmission. What you will use will depend upon the situation.

Magnetism

In order to understand the basics of a generator, we need to make a small diversion into the field of magnetism. Everyone who owns a refrigerator is familiar with magnetism, as it is the force that keeps all papers stuck to the side of it (with the exception of the occasional jelly smudge left by your sloppy roommate, or by you, if you are the sloppy roommate). Magnetism, though, is not just a recent phenomenon, as cultures thousands of years ago knew of its existence. Rocks such as lodestone naturally exhibit this force and have been used for some time for specialized purposes, such as in compasses to tell directions.

Anyone who has played with magnets for any amount of time has noticed that they have two poles. These poles, designated north and south, exhibit one property similar to charged particles: like poles are repulsive, and unlike poles are attractive. This property, though, causes a tremendous amount of confusion between electricity and magnetism, as some people will confuse the two for being the same. The magnetic and electrostatic forces are not the same. The north pole of a magnet will apply a force on a magnet that is placed near it; it will not, however, apply any force on a charged particle that is placed near it.

This is not to say that the magnetic and electrostatic forces or not related. It turns out that they are actually manifestations of the same force: the electromagnetic force. We can see that connection whenever we move a magnet or a charged particle. This connection was discovered Hans Oersted in 1820 when he noticed that a constant electrical current generated a magnetic field. This field was found to run in a circular pattern around the wire, with the current as the center of the circle. When Oersted placed static magnets around the wire, he found the presence of a current in the wire created a force that pushed on the magnets and rearranged them. Thus, he found that a moving charge can have a force on a static magnet.

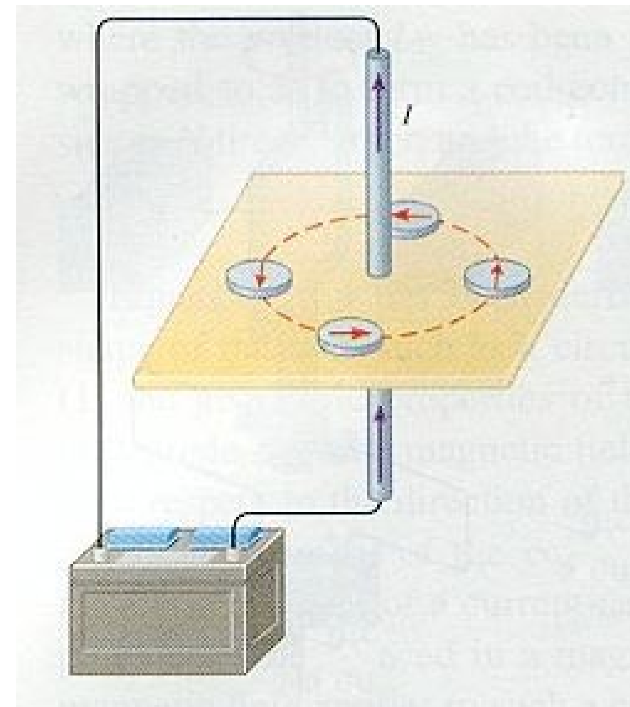


Fig. 9: Oersted's experiment

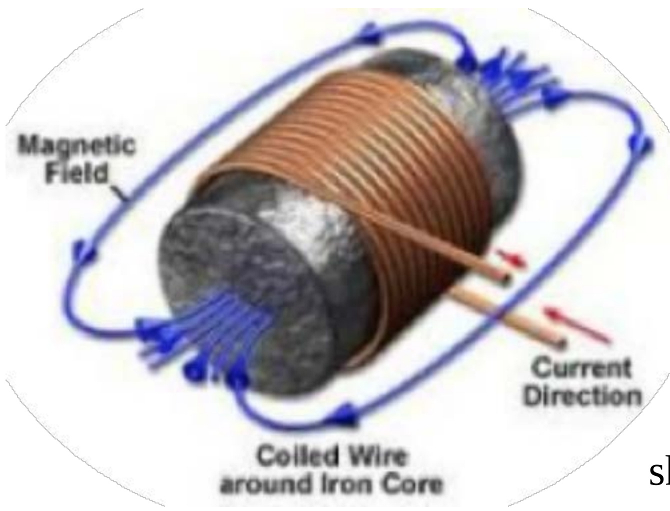


Fig. 10: solenoid

While Oersted's discovery was very simple, it had far-reaching implications. Instead of relying on nature to provide natural magnets, it was now possible to create magnets of any size and shape by merely twisting wires in various shapes and applying the appropriate current. The magnetic field discovered by Oersted was not particularly useful, as it dropped off as 1/distance as you moved away from the wire and ran in circles around the wire. If the wire is wound into a coil instead, the magnetic field inside of the coil is constant and depends only on the current and the number of windings per distance. This field can be enhanced by placing an iron bar in the middle of the coil by factors of a thousand. This is extremely useful, as it looks a great deal like a bar magnet, but has the added advantage that it can be turned off by stopping the current. This solenoid is used extensively, such as the valves in your washing machine and the starter in your car.

Electromagnetic Induction and Generators

Oersted's discovery led to further discoveries by other scientists. Upon hearing about Oersted's find, Englishman Michael Faraday set about creating the first motor in 1821. The idea behind this is quite simple. If a moving charge can create a field that will apply a force on a magnetic, then Newton's Third Law states that a magnet must have a force on a moving charge.

By choosing the orientation of the current and magnet correctly (due to the direction of the magnetic field created by a moving charge, the applied magnetic field and the particle velocity must be perpendicular to each other, which will create a force perpendicular to both of these; see Figure 11), one can create a force on the magnet that will cause it to accelerate. For a DC motor, you must wind the wire into coils that are positioned to be perpendicular to the magnets, as well as creating a slotted slip ring that allows the current to switch direction in the coils once it has turned through 180 degrees.

Faraday did not stop with his creation of the homopolar motor. He continued to study electricity and magnetism for a decade in order to learn more secrets about how it operates. In 1831, he published his work on law of electromagnetic induction. The idea behind this law comes directly from the discussion above. Imagine a constant current that is flowing in a straight wire past a magnet that is oriented in a perpendicular fashion relative to the current. As we stated, there will be a force between the two.

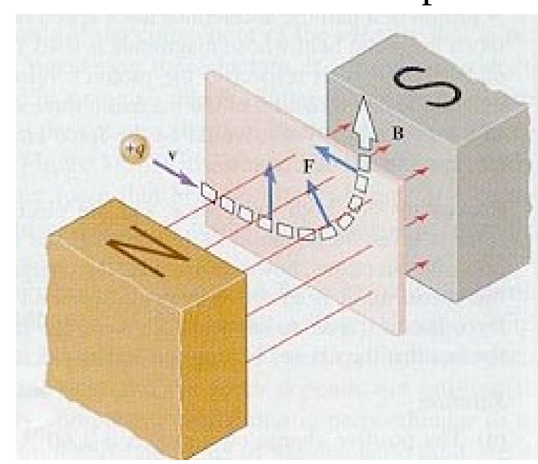


Fig. 11: charged particle moving between magnets

However, the Theory of Relativity says that all inertial (constant velocity) reference frames are equivalent. In other words, the electron moving past the magnet should be the same as the electron being still and having the magnet move past it at a constant velocity. Since the first scenario led to a force between the two, so must this second, which means a moving magnet creates a force on a static charged particle. The only way that this could occur is if the moving magnet is creating an electric field that interacts with the static charge. Therefore, a moving magnetic must induce an electric field as it changes the magnetic field in a particular location.

This is the basis behind the operation of a generator. Figure 12 shows one possible diagram for a generator. In the configuration shown, a wire coil is spun on an axle in a magnetic field. As the electrons in the wire move through the magnetic field, they experience a force that is perpendicular to their motion. This force causes them to move along the wire, thus creating a current. There are many other possible configurations for a generator, but they operate on the same basic principle. As long as the axle is connected to a kinetic energy source, the generator will produce an electrical current.

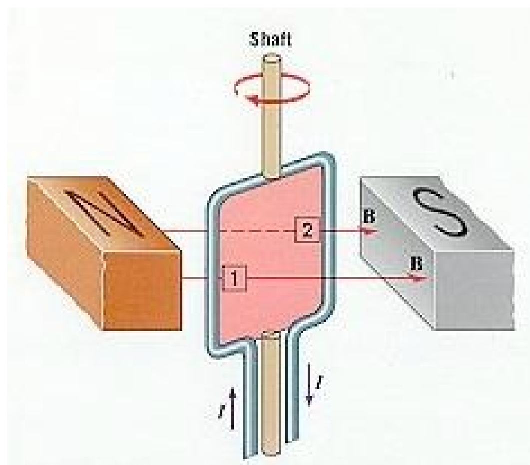


Fig. 12: generator diagram

The importance of Faraday's discovery cannot be underestimated. At the beginning of this chapter, we talked about creating electric fields to accelerate electrons and create currents. The way we talked about doing this was with a chemical battery. Now, we have a way to take kinetic energy (moving a magnet or a wire) and create an electric field to do the same thing. Faraday's electromagnetic induction law is the basis of every generator we use throughout the world to create the electricity that we use in our houses.

So, to summarize: static charge particles only create electric fields, and static magnets only create magnetic fields. Moving charged particles create both fields, as do moving magnets. What Oersted's and Faraday's discoveries led to was the fact that electricity and magnetism are just two different manifestations of the same force, and that they are intimately tied together.

Electrical Energy and Power

As stated before, currents carry kinetic energy through the wire. In Equation 3.3, we saw that the amount of potential energy is given by the amount of charge times the electric field times the distance through which the charge moves. Later, we defined the electric potential V in terms of the electric field and the distance through which the charge travels. If we combine those two equations, we get that the change in energy for a particle that goes through a potential V is

(Equn. 3.6)

$$\Delta E = qV$$

While this equation is useful from the standpoint of describing electrical energy, it is not of much practical use for our everyday life. The reason for this is due to the way that we use energy. Most electrical appliances that we use are rated by their power rating, and not their energy usage. As an example, look at a light bulb. Somewhere on the bulb, there will be printed the wattage, or power rating, of the bulb. We know from Chapter 1 that the power is related to the change in energy by $P = \Delta E/\Delta t$. If the voltage is not varying with time, or if we look at the average power for an alternating voltage, we can combine this formula with Equation 3.6 to get

(Equn. 3.7)

$$P = \Delta E/\Delta t = (q \times V)/\Delta t = (q/\Delta t)\,V$$
$$P = I\,V$$

since the current is the amount of charge per unit time past a point. This is a very useful equation to know, as it allows us to convert between the three variables as long as two of the variables in the equation are known. (Video EXAMPLE)

For instance, suppose a 500-watt microwave oven is plugged into a 110-V outlet. We can solve for the amount of current that the microwave draws by rewriting Equation 3.7 as

$I = P/V = (500\text{ W})/(110\text{ V}) = 4.5\text{ A}$

This is a considerable amount of current to send to an appliance, especially if this is not the only appliance that is plugged into this circuit and operating. Other appliances will also be drawing current if they are on, and all of this current must go through the wires through the wall. As we previously stated, this can present a problem if the total current gets too large, as the wire has its own resistance. This resistance will extract power from the flow.

To determine how much, we must combine Equations 3.5 and 3.7. Ohm's Law allows us to determine the potential difference across a wire that has a resistance R through which a current I is flowing ($V = IR$). If we plug this voltage into Equation 3.7, we get that the power lost in the wire is given by

(Equn. 3.8)

$$P_{lost} = I^2R$$

Suppose the wire leading to the microwave has a resistance of 1 Ω (a fairly small value). With this tiny resistance, the power being lost to heat in the system is (Video EXAMPLE)

$P = (4.5\text{ A})^2\, 1\,\Omega = 20\text{ W}$

Thus, the total power that will need to be supplied to the system is really 520 W, as the microwave will use 500 W, and the wire will lose 20 W. This gives a net efficiency of 500W/520W = .96 = 96%.

This example shows one of the problems with our current system of supplying electricity to homes from centralized power plants. Electricity will be lost in the wires that send current no

matter how long. In this example, we have only considered that wire in the house. Think about the miles and miles of wire that are required to get the electricity to our homes from the generating facility. In modern America, that generating facility can by tens if not hundreds of miles away. As we go to more renewable energy such as windmills, this electricity might come from thousands of miles away. Even small resistances per mile (example .2 Ω /mile) can lead to large losses.

How do we transmit it so far without losing everything? This is where transformers come into play. In equation 3.8, we can do very little about the resistance of the wire. If we try to decrease it by making the wire thicker, we will increase the weight of it and cause it to snap. Besides, the largest term in the equation is the current term, as it is squared. If we can reduce the current that we have to send over long distances, then we can greatly reduce the amount of power lost. To do this and still get the same amount of power delivered, we have to go back to Equation 3.7. We can deliver the same amount of power by increasing the voltage while we decrease the current. As an example, a 10 amp current at 40 V delivers the same amount of power as a 1 amp current at 400 V.

$P = IV = (10\ A)(40\ V) = 400\ W$
$= (1\ A)(400\ V)$

However, the amount of power lost in those two situations through a 1 Ω wire is drastically different.

$P_{lost\ 1} = (10\ A)^2\ 1\ \Omega = 100\ W$

$P_{lost\ 2} = (1\ A)^2\ 1\ \Omega = 1\ W$

As you can see, the first situation loses 100 times what the second situation does in resistive heat. That is the key to our transmission system in the U.S. We generate power at the plant at very high voltages (megavolts) and transmit it over long distances to your city or town. There, the voltage is reduced via transformers to kilovolts and sent over shorter lines to your neighborhood. The substation in your neighborhood reduces the voltage even more down to 440 V. Near you house, there is one last transformer that reduces it to 220 V. At your house, you either use this or split it to receive 110 V in your everyday receptacles.

How a transformer changes voltages relies heavily on Faraday's Induction Law and solenoids. When we talked about the

Induction Law earlier, we talked about it in terms of moving magnets. However, the only thing that needs to happen to induce an electric field is a changing magnetic field. We can provide this with a solenoid and an alternating current. If you remember, the magnetic field within a solenoid is constant and depends upon the current and the number of turns in the solenoid. If we supply an alternating current to the solenoid, it will create an alternating magnetic field. Placing a second solenoid with a different number of turns near the mouth of the first solenoid will induce an electric potential in the second solenoid that will depend on the strength of the magnetic field and the number of turns in the second solenoid. By judiciously choosing the number of turns in both solenoids, one can either step up or step down the voltage as long as an alternating current is used. It is for this reason that we use AC in the U.S. for electricity generation, as DC will not work with a transformer. In doing so, we limit the amount of energy lost to transmission of electricity to about 10% of the total energy originally created.

Problems

1. A carbon atom has 6 protons in the nucleus. If the innermost electron in a carbon atom is 1.0 x 10-10 m away from the nucleus, what is the force of attraction between the electron and the nucleus?
2. Two copper wires have different thicknesses, but the same length. Wire A has a radius of 1/16th of an inch, while Wire B has a radius of 1/8th of an inch. How does the resistance of Wire A compare to that of Wire B?
3. Two aluminum wires have different lengths, but the same thicknesses. If Wire C is twice as long as Wire D, how do their resistances compare?
4. A 20.0 Ω light bulb is connected to a 12 V battery. How much current flows through the light bulb?
5. An electric stove requires 5,500 W of power to operate.
   a) If it operates at 220 V, how much current does it draw?
   b) If the wire running into the stove has a resistance of 2 Ω, how much power is lost in the wire due to resistance?
6. An appliance with a resistance of 4 Ω is placed in parallel with one that has a resistance of 8 Ω. They are connected to a 10 V source.
   a) What is the equivalent resistance of the circuit?
   b) How much current runs through each appliance?
7. The appliances in Problem 6 are connected in series.
   a) What is the equivalent resistance of the circuit?
   b) How much current runs through each appliance?
8. An evil mastermind is firing a charged particle gun right at you. How do you deflect the beam away from you?