Chapter 5

Electrical Energy

Our modern technological society is largely defined by our widespread use of electrical energy. Electricity provides us with light, heat, refrigeration, communication, elevators, and entertainment. We are so dependent on electricity that when it is unavailable for even a few minutes, the word "crisis" comes to mind. Electrical energy is popular because it is so easily transmitted from one place to another, and converted into other forms of energy.

The concepts and principles of electricity are beautiful and intricate, but this is hardly the place to present them in complete detail. For a more thorough treatment of the subject, you can consult almost any standard introductory physics textbook.

Electric Charge

The simplest electrical phenomenon is **static electricity**, the temporary "charging" of certain objects when they are rubbed against each other. Run a comb through your hair when it's dry, and the hair and comb begin to attract each other, indicating that they are charged. Other familiar examples include clothes sticking together in the dryer, and the sudden shock that you sometimes get when shaking someone's hand after walking across a carpet with rubber-soled shoes.

What you may not have noticed is that static electricity can result in both attractive and repulsive forces. The comb attracts the hair and vice-versa, but the hairs repel each other, and two combs similarly charged will likewise repel each other. To explain this we say that there are two types of electric charge, called positive and negative. When objects become charged by rubbing against each other, one always becomes positive and the other becomes negative. Positively charged objects (the hair, for instance) attract negatively charged objects (the comb) and vice-versa, but two positives repel each other, as do two negatives. In summary, like charges repel, while unlike charges attract.

What's happening at the atomic level is this: All atoms contain particles called protons and electrons, which carry intrinsic positive and negative charges, respectively. Ordinarily, the number of protons in a chunk of matter is almost exactly equal to the number of electrons, so their static-electricity effects cancel out on large scales. However, rubbing certain objects together transfers some of the electrons from one to the other, leaving the first object positively charged (because it now has has an excess of protons) and the other object negatively charged (because it now has an excess of electrons).

In the official scientific system of units, the amount of electric charge on an object is measured in units called **coulombs** (abbreviated C). The total charge on all the protons in a gram of matter is typically about 50,000 C, while the electrons in the same gram of matter would carry a total charge of $-50,000$ C. These numbers may seem inconveniently large, but they're not very relevant to everyday life because all we normally measure is the *excess* of one type of charge over the other. The amount of excess charge that readily builds up on a person's hair is less than a *micro*coulomb, that is, 0.000001 C. ("Micro" is the metric prefix for a millionth, 0.000001.) The charge of a single proton turns out to be 1.6×10^{-19} C, while the charge of a single electron is minus the same amount. Thus, the number of excess electrons on a charged comb is quite enormous, but only a tiny, tiny fraction of all the electrons in the comb.

How long an object remains electrically charged depends on how easily the excess electrons can find their way back to the excess protons. Some materials, such as metals, allow electrons to move through them quite readily, while other materials, such as paper, plastic, and dry air, offer quite a bit of resistance to the motion of electrons. Materials in the first class are called **conductors**, while materials in the second class are called **insulators**. The distinction between conductors and insulators is merely a matter of degree, however; all materials conduct to some extent. Furthermore, any insulating material will become a good conductor if it is subjected to electrostatic forces that are strong enough to rip electrons out of the atoms. The most dramatic example is lightning: the sudden discharge of thunderclouds through a column of air, which is momentarily made into a conductor by the enormous static charges. The shock that you get when you shake someone's hand is the same phenomenon, on a much smaller scale.

Electric Circuits

Although static electricity has its useful applications, more useful by far is a system that can *continuously* separate negative from positive charges, then extract energy from them as they move around to recombine. This is the principle of the **electric circuit**. Figure 5.1 shows a very simple electric circuit, consisting of a battery with its two ends connected by a single wire.

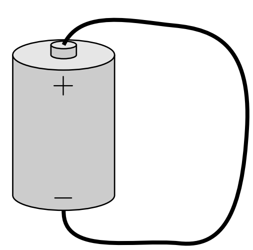

Figure 5.1. A very simple electric circuit, consisting of a battery with its two ends connected by a metal wire. (Don't try this at home unless you don't mind running down the battery very quickly.)

The battery uses chemical energy to separate negative from positive charges, always maintaining a slight excess positive charge on its "+" end and a slight excess negative charge on its "−" end. When the battery isn't connected to any conductors, these excess charges just sit there and do nothing of interest. Connect the two ends together with a metal wire, however, and the electrons will move along the wire in order to recombine with the protons. Along the way, they will collide with the atoms in the wire, creating a kind of "friction" that makes the wire get hot. The battery, meanwhile, keeps replenishing the supply of electrons at its negative end, until its internal chemical reaction has gone to completion. In summary, this circuit converts chemical energy in the battery into electrical energy, which is then converted into thermal energy in the wire.

Figure 5.2 shows a slightly more complicated circuit, consisting of a battery, a pair of wires, and an ordinary incandescent light bulb. This circuit is essentially a flashlight. Because the filament of the bulb offers significantly more resistance to the flow of electrons than do the wires leading to it, the electrons will flow much more slowly in this circuit than in the previous one. Instead of creating thermal energy uniformly along the wires, this circuit concentrates the thermal energy at the point of greatest resistance, the filament. The filament becomes so hot that it glows. The bulb around the filament keeps oxygen out, preventing chemical reactions of the hot metal filament with oxygen.

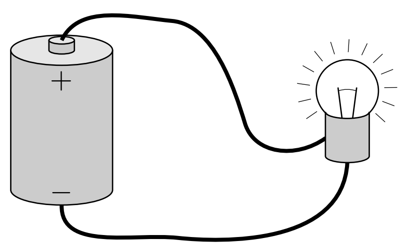

Figure 5.2. A "flashlight" circuit, consisting of a battery connected to a light bulb by a pair of wires. (The connections inside the bulb simply route the electric current through the filament.)

To understand electric circuits quantitatively, we need to know a little more about the battery. It turns out that a fresh battery, under most uses, provides a *fixed* amount of electrical energy to each electron that it pushes around the circuit. This means that it provides a fixed amount of energy to each coulomb of electric charge that moves around the circuit, and that two coulombs of charge receive twice as much energy as one coulomb of charge. The amount of energy provided, per coulomb of charge moved, is called the battery's **voltage**:

$$\text{battery voltage} = \frac{\text{energy provided}}{\text{amount of charge}}. \tag{5.1}$$

The standard unit of voltage is therefore the joule per coulomb, a unit that has its own name, the **volt** (V):

$$1 \text{ volt} = 1 \, \frac{\text{joule}}{\text{coulomb}}. \tag{5.2}$$

According to equation 5.1, if you know the voltage of a battery and want to know how much energy it has released, you need to multiply by the amount of charge that it has moved:

$$\text{energy provided} = (\text{battery voltage}) \times (\text{amount of charge}). \tag{5.3}$$

For example, if a 12-volt car battery pushes 100 coulombs of charge out its terminal, it has provided 1200 joules of energy.

Very often, instead of talking about the *total* amount of charge pushed through a circuit element, we talk about the amount of charge that passes a given point *per unit time*. This quantity is called the **electric current**:

$$\text{current} = \frac{\text{amount of charge passing}}{\text{time elapsed}}. \tag{5.4}$$

The standard unit of current is the coulomb per second, which is also called the **ampere** (or simply **amp**, abbreviated A):

$$1 \text{ ampere} = 1\ \frac{\text{coulomb}}{\text{second}}. \tag{5.5}$$

For example, if 20 coulombs of charge pass by a point during a time of 5 seconds, the current would be 20/5 coulombs per second, or 4 amperes.

Currents of a few coulombs per second are quite common in electric circuits, even though a coulomb would be considered a huge amount of charge, were it unbalanced by an equal amount of opposite charge. In electrical wires, the negative charge of the moving electrons is almost exactly balanced, at every point, by the positive charge of the stationary protons.

In a single-loop circuit such as those shown in Figures 5.1 and 5.2, the value of the current will be the same at every point around the loop. Otherwise, unbalanced charges would be building up somewhere in the circuit, and this could never continue for more than a split-second, because those charges would repel each other with huge electrostatic forces.

How can you predict how much current will flow in a given circuit? This is determined by two things: the voltage of the battery (or equivalent energy source) and the amount of **resistance** offered by the wires, filaments, and whatever else the electrons must pass through during their journey. The technical definition of resistance is simply the number of volts required, per ampere of current desired:

$$\text{resistance} = \frac{\text{volts required}}{\text{current desired}} \qquad \text{(definition of resistance)}. \tag{5.6}$$

A typical copper wire has relatively low resistance (not many volts required to push lots of current through it), while the filament of a light bulb has a moderately high resistance (quite a few volts required per ampere of current desired). Turning equation 5.6 around gives

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}. \tag{5.7}$$

This simply says that the greater the voltage, the greater the current, while the greater the resistance, the smaller the current.

The unit of resistance would be the volt per ampere, which also has its own name, the **Ohm** (abbreviated by Ω, the capital Greek letter omega). A typical flashlight bulb has a resistance of about 10 ohms, so when you connect it to a 3-volt power source (a pair of 1.5 V batteries), you get a current of

$$\text{current} = \frac{3\ \text{V}}{10\ \Omega} = 0.3\ \text{A}. \tag{5.8}$$

The Plumbing Analogy

For better intuitive understanding of electric circuits, I often use a popular analogy between electrons flowing through wires and water flowing through pipes. In this analogy, voltage corresponds to pressure, while current corresponds to the rate at which the water is flowing (in gallons per minute, perhaps). A battery is like a pump that tries as hard as it can to maintain a constant level of pressure, no matter how fast the water is allowed to flow. A resistive element like a light bulb is analogous to a constriction in the pipe, where there's only a tiny hole for the water to pass through. And a switch, which you can open in order to "break" a circuit, is like a valve that you close to cut off the flow of water.

This analogy can help with guessing the answers to many basic questions about electricity. Can you have high voltage but no current? Sure: In the plumbing analogy, this would be like having high pressure but no flow of the water. That's easy if you just close a valve to block the flow, or in the electrical case, open a switch to block the flow of electrons. Can you have high current but no voltage? No: That would be like having lots of water flowing with no pressure behind it. Why is there no delay between when you flip the switch and the lights come on? Well, in the plumbing analogy, that would be like opening a valve and immediately seeing water come out the other end of the hose. But of course that can happen, provided that the hose is already full of water. Apparently, electrical wires are already full of electrons, ready to move at a moment's notice when a voltage is applied.

Energy and Power

As already mentioned, voltage is energy per unit charge, so if you want to know how much energy has been provided by a battery, you simply multiply the voltage by the amount of charge that it has moved so far (see equation 5.3). The same formula gives the amount of electrical energy *used* by a light bulb or any other device that consumes electrical energy, provided that you replace the battery voltage by the voltage *difference* between one end of the device and the other:

$$\text{energy used} = (\text{difference in voltage}) \times (\text{charge passing through}). \tag{5.9}$$

(In a complicated circuit, there may be other devices between your device and the battery, so the difference in voltage "seen" by your device may not be the full battery voltage.) If instead of multiplying by the amount of charge, we multiply by the *current* passing through the device, we get

$$\begin{aligned}(\text{voltage difference}) \times (\text{current}) &= (\text{voltage difference}) \times \frac{\text{charge}}{\text{time}} \\ &= \frac{\text{energy}}{\text{time}} = \text{power}.\end{aligned} \tag{5.10}$$

That is, the product of the voltage times the current gives the *rate* at which your device absorbs electrical energy. For instance, if 0.3 amperes of current are flowing through a flashlight bulb due to a 3-volt voltage difference across it, the rate at which it uses electrical energy is

$$(3 \text{ V})(0.3 \text{ A}) = 0.9 \text{ V}\cdot\text{A} = 0.9 \frac{\text{J}}{\text{C}}\cdot\frac{\text{C}}{\text{s}} = 0.9 \frac{\text{J}}{\text{s}} = 0.9 \text{ W}, \tag{5.11}$$

or just under one watt. If you leave this flashlight on for one hour, the total energy used is then

$$\text{energy} = (\text{power}) \times (\text{time}) = (0.9 \text{ W})(3600 \text{ s}) = 3240 \text{ J} \approx 3000 \text{ J}. \tag{5.12}$$

The total chemical energy that can be extracted from a pair of flashlight batteries must be only a few times greater than this, because we all know that the batteries will power the flashlight for only a few hours before going dead.

Exercise 5.1. Suppose you wish to make a 1500-watt electric heater that plugs into an ordinary 115-volt outlet. To do so, all you need is a piece of wire with the correct resistance. (The type of wire normally used is called "nichrome".) Calculate the amount of current (in amperes) that should flow through the wire to produce 1500 watts of power. Then use this result to calculate the required resistance, in ohms.

Exercise 5.2. Suppose that you run a 1500-watt electric heater for three hours per day, every day for a month. How many kilowatt-hours of electricity have you used (in a month)? If electricity costs 7 cents per kilowatt-hour, how much will you pay for this amount of electricity?

Exercise 5.3. The circuit breakers in your home are intended to limit the current on any circuit to a safe level, usually 20 amperes. The voltage in these circuits is approximately 115 volts. How many 100-watt lightbulbs could you connect to this circuit, before the breaker automatically shuts off the current? (Hint: First compute how much current is required by each bulb.)

Exercise 5.4. The news reports tell us that the western U.S. has been running short of electric power at times of peak use. Suppose that every household in the western states were to replace its most-used incandescent lightbulb with a compact fluorescent bulb that uses only 1/4 as much electricity. Estimate how many megawatts of power this would save, over the entire region, during the peak evening time period. Would you call this amount of power significant? (Hints: You'll need to estimate the number of watts saved per bulb and the number of households in the western states. Look up any population statistics that you need. Other factors that you *may* want to consider: What fraction of people use their electric lights on a typical evening? What fraction of these households have electric heat, which would have to make up for the smaller heat output of the fluorescent bulbs?)