CHAPTER 19
Electrical Circuits

Figure 19.1 Electric energy in massive quantities is transmitted from this hydroelectric facility, the Srisailam power station located along the Krishna River in India, by the movement of charge—that is, by electric current. (credit: Chintohere, Wikimedia Commons)

Chapter Outline

INTRODUCTION The flicker of numbers on a handheld calculator, nerve impulses carrying signals of vision to the brain, an ultrasound device sending a signal to a computer screen, the brain sending a message for a baby to twitch its toes, an electric train pulling into a station, a hydroelectric plant sending energy to metropolitan and rural users—these and many other examples of electricity involve electric current, which is the movement of charge. Humanity has harnessed electricity, the basis of this technology, to improve our quality of life. Whereas the previous chapter concentrated on static electricity and the fundamental force underlying its behavior, the next two chapters will be devoted to electric and magnetic phenomena involving current. In addition to exploring applications of electricity, we shall gain new insights into the workings of nature.

19.1 Ohm's law

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe how current is related to charge and time, and distinguish between direct current and alternating current
- Define resistance and verbally describe Ohm’s law
- Calculate current and solve problems involving Ohm’s law

Section Key Terms

alternating current	ampere	conventional current	direct current	electric current
nonohmic	ohmic	Ohm’s law	resistance	

Direct and Alternating Current

Just as water flows from high to low elevation, electrons that are free to move will travel from a place with low potential to a place with high potential. A battery has two terminals that are at different potentials. If the terminals are connected by a conducting wire, an electric current (charges) will flow, as shown in Figure 19.2. Electrons will then move from the low-potential terminal of the battery (the *negative* end) through the wire and enter the high-potential terminal of the battery (the *positive* end).

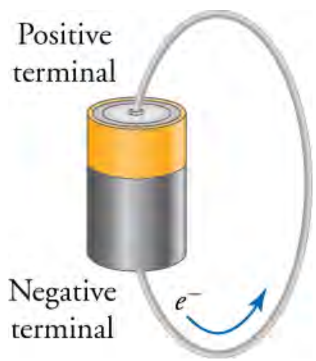


Figure 19.2 A battery has a wire connecting the positive and negative terminals, which allows electrons to move from the negative terminal to the positive terminal.

Electric current is the rate at which electric charge moves. A large current, such as that used to start a truck engine, moves a large amount very quickly, whereas a small current, such as that used to operate a hand-held calculator, moves a small amount of charge more slowly. In equation form, electric current I is defined as

$$I = \frac{\Delta Q}{\Delta t}$$

where ΔQ is the amount of charge that flows past a given area and Δt is the time it takes for the charge to move past the area. The SI unit for electric current is the ampere (A), which is named in honor of the French physicist André-Marie Ampère (1775–1836). One **ampere** is one coulomb per second, or

$$1 \text{ A} = 1 \text{ C/s}.$$

Electric current moving through a wire is in many ways similar to water current moving through a pipe. To define the flow of water through a pipe, we can count the water molecules that flow past a given section of the pipe. As shown in Figure 19.3, electric current is very similar. We count the number of electrical charges that flow past a section of a conductor; in this case, a wire.

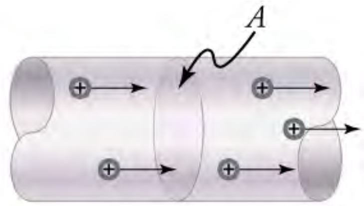


Figure 19.3 The electric current moving through this wire is the charge that moves past the cross-section A divided by the time it takes for this charge to move past the section *A*.

Assume each particle q in Figure 19.3 carries a charge $q = 1\ \text{nC}$, in which case the total charge shown would be $\Delta Q = 5q = 5\ \text{nC}$. If these charges move past the area A in a time $\Delta t = 1\ \text{ns}$, then the current would be

$$I = \frac{\Delta Q}{\Delta t} = \frac{5\ \text{nC}}{1\ \text{ns}} = 5\ \text{A}. \tag{19.1}$$

Note that we assigned a positive charge to the charges in Figure 19.3. Normally, negative charges—electrons—are the mobile charge in wires, as indicated in Figure 19.2. Positive charges are normally stuck in place in solids and cannot move freely. However, because a positive current moving to the right is the same as a negative current of equal magnitude moving to the left, as shown in Figure 19.4, we define **conventional current** to flow in the direction that a positive charge would flow if it could move. Thus, unless otherwise specified, an electric current is assumed to be composed of positive charges.

Also note that one Coulomb is a significant amount of electric charge, so 5 A is a very large current. Most often you will see current on the order of milliamperes (mA).

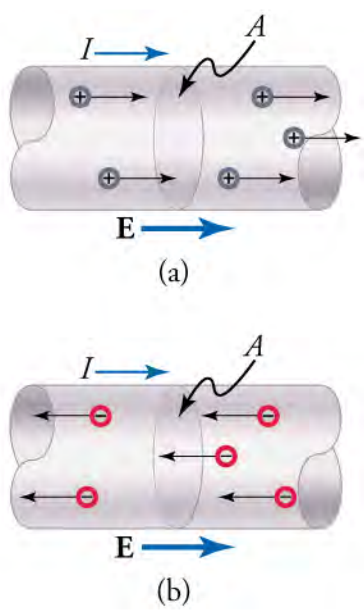


Figure 19.4 (a) The electric field points to the right, the current moves to the right, and positive charges move to the right. (b) The equivalent situation but with negative charges moving to the left. The electric field and the current are still to the right.

Snap Lab

Vegetable Current

This lab helps students understand how current works. Given that particles confined in a pipe cannot occupy the same space, pushing more particles into one end of the pipe will force the same number of particles out of the opposite end. This creates a current of particles.

Find a straw and dried peas that can move freely in the straw. Place the straw flat on a table and fill the straw with peas. When you push one pea in at one end, a different pea should come out of the other end. This demonstration is a model for an electric current. Identify the part of the model that represents electrons and the part of the model that represents the supply of electrical energy. For a period of 30 s, count the number of peas you can push through the straw. When finished, calculate the *pea current* by dividing the number of peas by the time in seconds.

Note that the flow of peas is based on the peas physically bumping into each other; electrons push each other along due to mutually repulsive electrostatic forces.

GRASP CHECK

Suppose four peas per second pass through a straw. If each pea carried a charge of 1 nC, what would the electric current be through the straw?

a. The electric current would be the pea charge multiplied by 1 nC/pea.
b. The electric current would be the pea current calculated in the lab multiplied by 1 nC/pea.
c. The electric current would be the pea current calculated in the lab.
d. The electric current would be the pea charge divided by time.

The direction of conventional current *is the direction that positive charge would flow*. Depending on the situation, positive charges, negative charges, or both may move. In metal wires, as we have seen, current is carried by electrons, so the negative charges move. In ionic solutions, such as salt water, both positively charged and negatively charged ions move. This is also true in nerve cells. Pure positive currents are relatively rare but do occur. History credits American politician and scientist Benjamin Franklin with describing current as the direction that positive charges flow through a wire. He named the type of charge associated with electrons negative long before they were known to carry current in so many situations.

As electrons move through a metal wire, they encounter obstacles such as other electrons, atoms, impurities, etc. The electrons scatter from these obstacles, as depicted in Figure 19.5. Normally, the electrons lose energy with each interaction. [1] To keep the electrons moving thus requires a force, which is supplied by an electric field. The electric field in a wire points from the end of the wire at the higher potential to the end of the wire at the lower potential. Electrons, carrying a negative charge, move on average (or *drift*) in the direction opposite the electric field, as shown in Figure 19.5.

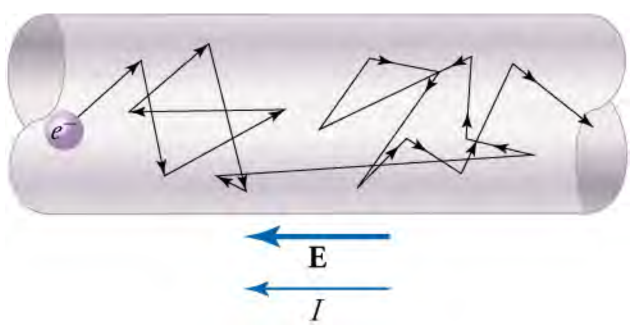


Figure 19.5 Free electrons moving in a conductor make many collisions with other electrons and atoms. The path of one electron is shown. The average velocity of free electrons is in the direction opposite to the electric field. The collisions normally transfer energy to the conductor, so a constant supply of energy is required to maintain a steady current.

So far, we have discussed current that moves constantly in a single direction. This is called **direct current**, because the electric charge flows in only one direction. Direct current is often called *DC* current.

Many sources of electrical power, such as the hydroelectric dam shown at the beginning of this chapter, produce **alternating current**, in which the current direction alternates back and forth. Alternating current is often called *AC current*. Alternating current moves back and forth at regular time intervals, as shown in Figure 19.6. The alternating current that comes from a normal wall socket does not suddenly switch directions. Rather, it increases smoothly up to a maximum current and then smoothly decreases back to zero. It then grows again, but in the opposite direction until it has reached the same maximum value. After that, it decreases smoothly back to zero, and the cycle starts over again.

1This energy is transferred to the wire and becomes thermal energy, which is what makes wires hot when they carry a lot of current.

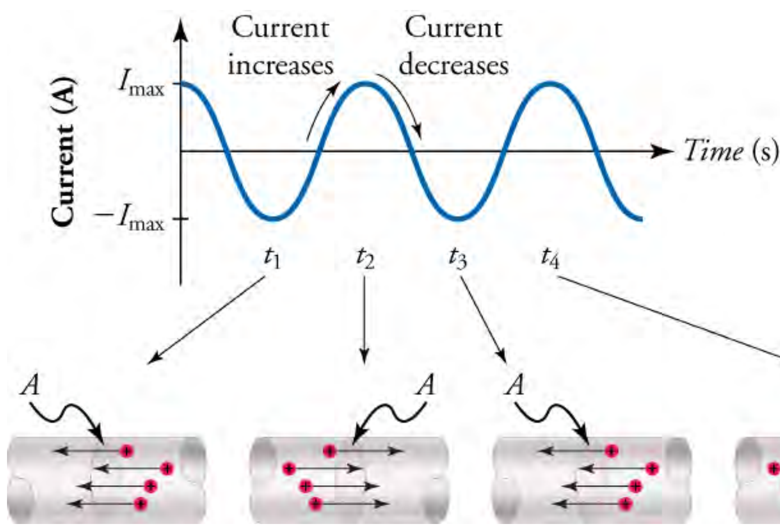


Figure 19.6 With alternating current, the direction of the current reverses at regular time intervals. The graph on the top shows the current versus time. The negative maxima correspond to the current moving to the left. The positive maxima correspond to current moving to the right. The current alternates regularly and smoothly between these two maxima.

Devices that use AC include vacuum cleaners, fans, power tools, hair dryers, and countless others. These devices obtain the power they require when you plug them into a wall socket. The wall socket is connected to the power grid that provides an alternating potential (AC potential). When your device is plugged in, the AC potential pushes charges back and forth in the circuit of the device, creating an alternating current.

Many devices, however, use DC, such as computers, cell phones, flashlights, and cars. One source of DC is a battery, which provides a constant potential (DC potential) between its terminals. With your device connected to a battery, the DC potential pushes charge in one direction through the circuit of your device, creating a DC current. Another way to produce DC current is by using a transformer, which converts AC potential to DC potential. Small transformers that you can plug into a wall socket are used to charge up your laptop, cell phone, or other electronic device. People generally call this a *charger* or a *battery*, but it is a transformer that transforms AC voltage into DC voltage. The next time someone asks to borrow your laptop charger, tell them that you don't have a laptop charger, but that they may borrow your converter.

WORKED EXAMPLE

Current in a Lightning Strike

A lightning strike can transfer as many as 10^{20} electrons from the cloud to the ground. If the strike lasts 2 ms, what is the average electric current in the lightning?

STRATEGY

Use the definition of current, $I = \frac{\Delta Q}{\Delta t}$. The charge ΔQ from 10^{20} electrons is $\Delta Q = ne$, where $n = 10^{20}$ is the number of electrons and $e = -1.60 \times 10^{-19}$C is the charge on the electron. This gives

$$\Delta Q = 10^{20} \times \left(-1.60 \times 10^{-19}\text{C}\right) = -16.0\ \text{C}. \tag{19.2}$$

The time $\Delta t = 2 \times 10^{-3}$s is the duration of the lightning strike.

Solution

The current in the lightning strike is

$$\begin{aligned} I &= \frac{\Delta Q}{\Delta t} \\ &= \frac{-16.0\ \text{C}}{2 \times 10^{-3}\text{s}} \\ &= -8\ \text{kA}. \end{aligned} \tag{19.3}$$

Discussion

The negative sign reflects the fact that electrons carry the negative charge. Thus, although the electrons flow from the cloud to the ground, the positive current is defined to flow from the ground to the cloud.

WORKED EXAMPLE

Average Current to Charge a Capacitor

In a circuit containing a capacitor and a resistor, it takes 1 min to charge a 16 µF capacitor by using a 9-V battery. What is the average current during this time?

STRATEGY

We can determine the charge on the capacitor by using the definition of capacitance: $C = \frac{Q}{V}$. When the capacitor is charged by a 9-V battery, the voltage across the capacitor will be $V = 9\ \mathrm{V}$. This gives a charge of

$$\begin{aligned} C &= \frac{Q}{V} \\ Q &= CV. \end{aligned} \tag{19.4}$$

By inserting this expression for charge into the equation for current, $I = \frac{\Delta Q}{\Delta t}$, we can find the average current.

Solution

The average current is

$$\begin{aligned} I &= \frac{\Delta Q}{\Delta t} \\ &= \frac{CV}{\Delta t} \\ &= \frac{(16 \times 10^{-6}\mathrm{F})(9\ \mathrm{V})}{60\ \mathrm{s}} \\ &= 2.4 \times 10^{-6}\mathrm{A} \\ &= 2.4\ \mu\mathrm{A}. \end{aligned} \tag{19.5}$$

Discussion

This small current is typical of the current encountered in circuits such as this.

Practice Problems

1. 10 nC of charge flows through a circuit in 3.0×10^{-6} s . What is the current during this time?
   a. The current passes through the circuit is 3.3×10^{-3} A.
   b. The current passes through the circuit is 30 A.
   c. The current passes through the circuit is 33 A.
   d. The current passes through the circuit is 0.3 A.

2. How long would it take a 10-mA current to charge a capacitor with $5.0\ \mathrm{mC}$?
   a. $0.50\ \mathrm{s}$
   b. $5\ \mathrm{ns}$
   c. $0.50\ \mathrm{ns}$
   d. $50\ \mu\mathrm{s}$

Resistance and Ohm’s Law

As mentioned previously, electrical current in a wire is in many ways similar to water flowing through a pipe. The water current that can flow through a pipe is affected by obstacles in the pipe, such as clogs and narrow sections in the pipe. These obstacles slow down the flow of current through the pipe. Similarly, electrical current in a wire can be slowed down by many factors, including impurities in the metal of the wire or collisions between the charges in the material. These factors create a resistance to the electrical current. **Resistance** is a description of how much a wire or other electrical component opposes the flow of charge through it. In the 19th century, the German physicist Georg Simon Ohm (1787–1854) found experimentally that current through a conductor is proportional to the voltage drop across a current-carrying conductor.

$$I \propto V$$

The constant of proportionality is the resistance R of the material, which leads to

$$V = IR(1.3).$$

This relationship is called **Ohm's law**. It can be viewed as a cause-and-effect relationship, with voltage being the cause and the current being the effect. Ohm's law is an empirical law like that for friction, which means that it is an experimentally observed phenomenon. The units of resistance are volts per ampere, or V/A. We call a V/A an *ohm*, which is represented by the uppercase Greek letter omega (Ω). Thus,

$$1\ \Omega = 1\ \text{V/A}(1.4).$$

Ohm's law holds for most materials and at common temperatures. At very low temperatures, resistance may drop to zero (superconductivity). At very high temperatures, the thermal motion of atoms in the material inhibits the flow of electrons, increasing the resistance. The many substances for which Ohm's law holds are called **ohmic**. Ohmic materials include good conductors like copper, aluminum, and silver, and some poor conductors under certain circumstances. The resistance of ohmic materials remains essentially the same for a wide range of voltage and current.

WATCH PHYSICS

Introduction to Electricity, Circuits, Current, and Resistance

This video presents Ohm's law and shows a simple electrical circuit. The speaker uses the analogy of pressure to describe how electric potential makes charge move. He refers to electric potential as *electric pressure*. Another way of thinking about electric potential is to imagine that lots of particles of the same sign are crowded in a small, confined space. Because these charges have the same sign (they are all positive or all negative), each charge repels the others around it. This means that lots of charges are constantly being pushed towards the outside of the space. A complete electric circuit is like opening a door in the small space: Whichever particles are pushed towards the door now have a way to escape. The higher the electric potential, the harder each particle pushes against the others.

GRASP CHECK

If, instead of a single resistor R, two resistors each with resistance R are drawn in the circuit diagram shown in the video, what can you say about the current through the circuit?

a. The amount of current through the circuit must decrease by half.
b. The amount of current through the circuit must increase by half.
c. The current must remain the same through the circuit.
d. The amount of current through the circuit would be doubled.

Virtual Physics

Ohm's Law

[Click to view content (http://www.openstax.org/l/28ohms_law)](http://www.openstax.org/l/28ohms_law)

This simulation mimics a simple circuit with batteries providing the voltage source and a resistor connected across the batteries. See how the current is affected by modifying the resistance and/or the voltage. Note that the resistance is modeled as an element containing small *scattering centers*. These represent impurities or other obstacles that impede the passage of the current.

GRASP CHECK

In a circuit, if the resistance is left constant and the voltage is doubled (for example, from $3\ \text{V}$ to $6\ \text{V}$), how does the current change? Does this conform to Ohm's law?

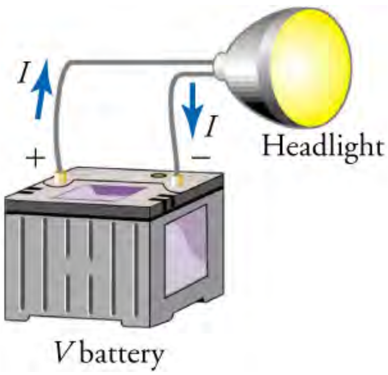
a. The current will get doubled. This conforms to Ohm's law as the current is proportional to the voltage.
b. The current will double. This does not conform to Ohm's law as the current is proportional to the voltage.

c. The current will increase by half. This conforms to Ohm's law as the current is proportional to the voltage.
d. The current will decrease by half. This does not conform to Ohm's law as the current is proportional to the voltage.

WORKED EXAMPLE

Resistance of a Headlight

What is the resistance of an automobile headlight through which 2.50 A flows when 12.0 V is applied to it?



STRATEGY

Ohm's law tells us $V_{\text{headlight}} = IR_{\text{headlight}}$. The voltage drop in going through the headlight is just the voltage rise supplied by the battery, $V_{\text{headlight}} = V_{\text{battery}}$. We can use this equation and rearrange Ohm's law to find the resistance $R_{\text{headlight}}$ of the headlight.

Solution

Solving Ohm's law for the resistance of the headlight gives

$$\begin{aligned} V_{\text{headlight}} &= IR_{\text{headlight}} \\ V_{\text{battery}} &= IR_{\text{headlight}} \\ R_{\text{headlight}} &= \frac{V_{\text{battery}}}{I} = \frac{12\text{ V}}{2.5\text{ A}} = 4.8\ \Omega. \end{aligned} \tag{19.6}$$

Discussion

This is a relatively small resistance. As we will see below, resistances in circuits are commonly measured in kW or MW.

WORKED EXAMPLE

Determine Resistance from Current-Voltage Graph

Suppose you apply several different voltages across a circuit and measure the current that runs through the circuit. A plot of your results is shown in Figure 19.7. What is the resistance of the circuit?

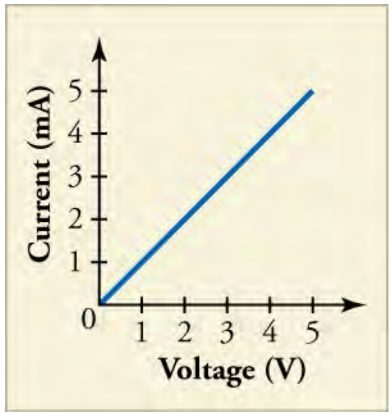


Figure 19.7 The line shows the current as a function of voltage. Notice that the current is given in milliamperes. For example, at 3 V, the current is 0.003 A, or 3 mA.

STRATEGY

The plot shows that current is proportional to voltage, which is Ohm's law. In Ohm's law ($V = IR$), the constant of proportionality is the resistance R. Because the graph shows current as a function of voltage, we have to rearrange Ohm's law in that form: $I = \frac{V}{R} = \frac{1}{R} \times V$. This shows that the slope of the line of I versus V is $\frac{1}{R}$. Thus, if we find the slope of the line in Figure 19.7, we can calculate the resistance R.

Solution

The slope of the line is the *rise* divided by the *run*. Looking at the lower-left square of the grid, we see that the line rises by 1 mA (0.001 A) and runs over a voltage of 1 V. Thus, the slope of the line is

$$\text{slope} = \frac{0.001\ \text{A}}{1\ \text{V}.} \tag{19.7}$$

Equating the slope with $\frac{1}{R}$ and solving for R gives

$$\begin{aligned} \frac{1}{R} &= \frac{0.001\ \text{A}}{1} \\ R &= \frac{1\ \text{V}}{0.001\ \text{A}} = 1{,}000\ \Omega \end{aligned} \tag{19.8}$$

or 1 k-ohm.

Discussion

This resistance is greater than what we found in the previous example. Resistances such as this are common in electric circuits, as we will discover in the next section. Note that if the line in Figure 19.7 were not straight, then the material would not be ohmic and we would not be able to use Ohm's law. Materials that do not follow Ohm's law are called **nonohmic**.

Practice Problems

3. If you double the voltage across an ohmic resistor, how does the current through the resistor change?
   a. The current will double.
   b. The current will increase by half.
   c. The current will decrease by half.
   d. The current will decrease by a factor of two.

4. The current through a $10\ \Omega$ resistor is 0.025 A. What is the voltage drop across the resistor?
   a. 2.5 mV
   b. 0.25 V
   c. 2.5 V
   d. 0.25 mV

Check Your Understanding

5. What is electric current?

a. Electric current is the electric charge that is at rest.
b. Electric current is the electric charge that is moving.
c. Electric current is the electric charge that moves only from the positive terminal of a battery to the negative terminal.
d. Electric current is the electric charge that moves only from a region of lower potential to higher potential.

6. What is an ohmic material?

a. An ohmic material is a material that obeys Ohm's law.
b. An ohmic material is a material that does not obey Ohm's law.
c. An ohmic material is a material that has high resistance.
d. An ohmic material is a material that has low resistance.

7. What is the difference between direct current and alternating current?

a. Direct current flows continuously in every direction whereas alternating current flows in one direction.
b. Direct current flows continuously in one direction whereas alternating current reverses its direction at regular time intervals.
c. Both direct and alternating current flow in one direction but the magnitude of direct current is fixed whereas the magnitude of alternating current changes at regular intervals of time.
d. Both direct and alternating current changes its direction of flow but the magnitude of direct current is fixed whereas the magnitude of alternating current changes at regular intervals of time.

19.2 Series Circuits

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Interpret circuit diagrams and diagram basic circuit elements
- Calculate equivalent resistance of resistors in series and apply Ohm's law to resistors in series and apply Ohm's law to resistors in series

Section Key Terms

circuit diagram	electric circuit	equivalent resistance
in series	resistor	steady state

Electric Circuits and Resistors

Now that we understand the concept of electric current, let's see what we can do with it. As you are no doubt aware, the modern lifestyle relies heavily on electrical devices. These devices contain ingenious **electric circuits**, which are complete, closed pathways through which electric current flows. Returning to our water analogy, an electric circuit is to electric charge like a network of pipes is to water: The electric circuit guides electric charge from one point to the next, running the charge through various devices along the way to extract work or information.

Electric circuits are made from many materials and cover a huge range of sizes, as shown in Figure 19.8. Computers and cell phones contain electric circuits whose features can be as small as roughly a billionth of a meter (a nanometer, or $10^{-9}\,\mathrm{m}$). The pathways that guide the current in these devices are made by ultraprecise chemical treatments of silicon or other semiconductors. Large power systems, on the other hand, contain electric circuits whose features are on the scale of meters. These systems carry such large electric currents that their physical dimensions must be relatively large.