15.2 Electric Current

SECTION OUTCOMES

- Define and describe electric current.
- Describe two conventions used to denote the direction of movement of electric charge.
- Use a circuit diagram to model and quantitatively predict the movement of elementary charge.

KEY TERMS

- current
- electron flow
- elementary charge
- open circuit
- closed circuit
- loads
- power supply
- circuit elements
- ammeter
- voltmeter
- series
- parallel

Volta's invention of the battery provided other scientists with a source of constant electric current for the first time. As a result, many other discoveries relating to current electricity followed quickly. Less than 25 years after Volta published his findings, scientists such as Ohm, Oersted, and Ampère published the results of their experiments, opening the door to the age of electricity.

Electric Current

To develop an understanding of the flow of electric charge, you can compare it to the flow of water. If you were asked to describe the flow of water over Niagara Falls, you might give your answer in litres per second or cubic metres per second. In an electric conductor, **current** (I) is described as a quantity of charge (q) passing a given point during an interval of time (Δt).

ELECTRIC CURRENT

Electric current is the quotient of the quantity of charge that moves past a point and the time interval during which the charge is moving.

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

Quantity	Symbol	SI unit
current	I	A (ampere)
amount of charge	q	C (coulomb)
time interval	Δt	s (second)

Unit Analysis

$$\frac{\text{coulomb}}{\text{second}} = \frac{\text{C}}{\text{s}} = \text{A}$$

Note: One coulomb per second is equivalent to one ampere.

Figure 15.6 In Niagara Falls, Ontario, the rate of water flow over the Canadian (Horseshoe) Falls is approximately 2.25×10^6 L/s.

MODEL PROBLEM

Electric Current and Charge

The electrical system in your home operates at a potential difference of 120.0 volts. A toaster draws 9.60 A for a period of 2.50 min to toast two slices of bread.

(a) Find the amount of charge that passed through the toaster.

(b) Find the amount of energy the toaster converted into heat (and light) while it toasted the bread.

Frame the Problem

- Power lines transport *electric energy* to your home and provide a constant *potential difference*.
- When the toaster is connected to the power source and turned on, the *potential difference* drives a *current* through the toaster elements.
- As *charges* pass through the element, *electric energy* is converted into *heat*.
- The amount of energy that was converted into heat is the same as the *change* in the *potential energy* of the *charges* as they pass through the toaster.

Identify the Goal

The amount of charge, q, that passes through the toaster elements in a given time

The amount of energy, ΔE_Q, converted into heat (and light)

Variables and Constants

Known	Unknown
$V = 120.0\ \text{V}$	q
$I = 9.60\ \text{A}$	ΔE_Q
$\Delta t = 2.50\ \text{min}$	

Strategy

Calculations

Use the definition for current to find the amount of charge.

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

Convert time to SI units.

$$2.5\ \cancel{\text{min}}\frac{60\ \text{s}}{\cancel{\text{min}}} = 150\ \text{s}$$

Substitute first

$$9.60\ \text{A} = \frac{q}{150\ \text{s}}$$

$$(9.60\ \text{A})(150\ \text{s}) = \frac{q}{\cancel{150\ \text{s}}}\cancel{150\ \text{s}}$$

$$q = 1440\ \text{A} \cdot \text{s}$$

$$q = 1440\ \text{C}$$

Solve for *q* first

$$(I)(\Delta t) = \frac{q}{\cancel{\Delta t}}\cancel{\Delta t}$$

$$q = (9.60\ \text{A})(150\ \text{s})$$

$$q = 1440\ \text{A} \cdot \text{s}$$

$$q = 1440\ \text{C}$$

1 A · s is equivalent to 1 C.

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(a) In 2.5 min, 1.44×10^3 C of charge pass through the toaster.

Strategy

Find the change in potential energy of the charges by using the definition of potential difference.

Calculations

$$V = \frac{\Delta E_Q}{q}$$

Substitute first

$$120\ \text{V} = \frac{\Delta E_Q}{1440\ \text{C}}$$

$$(120\ \text{V})(1440\ \text{C}) = \frac{\Delta E_Q}{\cancel{1440\ \text{C}}}\cancel{1440\ \text{C}}$$

Solve for ΔE_q first

$$Vq = \frac{\Delta E_Q}{\cancel{q}}\cancel{q}$$

$$\Delta E_Q = (120\ \text{V})(1440\ \text{C})$$

A V · C is equivalent to a J.

$$\Delta E_Q = 1.73 \times 10^5\ \text{V} \cdot \text{C}$$

$$\Delta E_Q = 1.73 \times 10^5\ \text{J}$$

$$\Delta E_Q = 1.73 \times 10^5\ \text{V} \cdot \text{C}$$

$$\Delta E_Q = 1.73 \times 10^5\ \text{J}$$

The toaster converted 1.73×10^5 J of electric energy into heat and light while it toasted the bread.

Validate

The units combined to give joules, which is correct for energy. Also, appliances that generate heat, such as a toaster, typically draw a larger current and consume more energy than devices that generate light, such as a light bulb.

PRACTICE PROBLEMS

4. A battery sends a 2.25 A current through a circuit for 1.50 min. If a total of 8.10×10^2 J of work was done by the current, what was the potential difference of the battery?

5. How long would it take a 17 V battery, sending a 5.0 A current through a circuit, to do 680 J of work?

6. How much work is done by a 25.0 V battery when it drives a 4.70 A current through a circuit for 36.0 s?

7. If a 160 V battery did 9.6×10^5 J of work in 2 min, what was the current?

8. A light draws a current of 0.48 A. How long must it be left on for charge of 36 C to pass through it?

9. An electric circuit draws 20 A. If the electric potential drop over the entire circuit is 120 V, calculate the total charge passing through the circuit in 1 h.

10. A cellular phone battery is recharged in 0.25 h after receiving 2.5×10^3 C of charge. Calculate the amount of electric current that the battery draws during recharging?

11. A physics student wishes to determine the amount of electric energy consumed in one day at his school as a result of classroom and hallway lighting. A quick survey revealed that there were approximately 200 40W fluorescent lights operating under a potential difference of 240 V for 16 hours each day. How much electric energy was used to light the school for one day?

Current versus Electron Flow

Although physicists began to study and use electric current around 1800, it was not until 1876 that an experiment at Harvard University showed that negative charges were moving in current-carrying conductors. It was another 25 years before J.J. Thomson (1856–1940) discovered the electron, and experiments demonstrated that the moving negative charges were electrons. By this time, the concept of a positive current was entrenched in scientific theory and literature. Fortunately, as long as you use a constant frame of reference, circuit analysis does not depend on knowing whether it is actually positive or negative charges that are moving. All measurable effects, such as the amount of energy transformed, are the same whether positive charges move one way or negative charges move the other way. Today, the term current (I) means the flow of positive charge (from anode to cathode) in a circuit. The flow of negative charge (from cathode to anode) is called **electron flow**. Since a wealth of theory was developed using positive current, the convention for analyzing circuits is still to use positive or conventional current.

Not all charges that move do so inside metals. In other media, either negative or positive (or both) charges can move. The aurora borealis lights up the sky when high-energy electrons from the sun collide with gas molecules in the air and are captured by Earth's magnetic field (see Figure 15.7).

In the process of electroplating with an aqueous salt solution such as silver cyanide (Figure 15.8), the positive silver ions (Ag^+) are attracted to the negative electrode, and the negative cyanide ions (CN^-) are attracted to the positive electrode.

Figure 15.7 The aurora borealis

COURSE CHALLENGE: SPACE-BASED POWER

Investigate the efficiency of photovoltaic cells using a small electric toy and photovoltaic cells from a local electronics shop.

Figure 15.8 A less expensive metal can be silver-plated to produce an attractive and corrosion-resistant surface. The object to be plated is connected to a circuit as the cathode. It is suspended in a solution containing silver cyanide. The silver ions are attracted to the cathode, where they combine with electrons and become solid silver atoms that remain permanently attached to the surface of the cathode.

PHYSICS FILE

During the last 20 years of the 1800s, physicists discovered that light had the ability to cause certain metals to emit negative charges. By 1905, Albert Einstein had created an hypothesis for the cause of, and formulated a law for, the photoelectric effect. In 1916, Robert Andrews Millikan carried out very careful and precise experiments in which he confirmed Einstein's predictions. In 1921, Einstein was awarded the Nobel Prize for "services to Theoretical Physics and the discovery of the law of the photoelectric effect."

Current and the Elementary Charge

Robert Andrews Millikan (1868–1953), a U.S. physicist, won the Nobel Prize in Physics in 1923 for his discovery of the elementary charge and for his research on the photoelectric effect. In 1917, his "oil-drop experiment" revealed that the static charge on a microscopic oil drop was always a whole-number (integral) multiple of a minute electric charge that was fixed in size. He concluded that the minute charge was the smallest size in which electric charge could be found. He designated this minute amount of charge the **elementary charge** (e). His measurements revealed that the size of one elementary charge is $e = 1.60 \times 10^{-19}$ C. (The most precise measurement to date is $e = 1.602\ 177\ 33 \times 10^{-19}$ C.) Today, one elementary charge is known to be the magnitude of the charge on a proton (+1 e) or an electron (–1 e).

When J.J. Thomson (see Figure 15.9) discovered the electron in 1897, he was able to measure only the ratio of the charge to the mass. Many scientists were sceptical about Thomson's proposed charge-carrying particle. They still thought that electric charge might be a fluid that could be divided into infinitely small pieces. However, when Millikan performed his oil-drop experiment in 1917, he established that when charge moved, it moved only as integral (whole-number) multiples of the elementary charge (e), just as water must be moved by at least one molecule at a time. He confirmed Thomson's hypothesis. Scientists now know that every quantity of charge can be expressed as an integral number of elementary charges.

Figure 15.9 J.J. Thomson devised ingenious experiments showing that the mysterious "rays" that caused phosphorus to glow, were in fact, tiny identical particles — he had discovered the electron. Most televisions still use this technology.

ELEMENTARY CHARGE

The amount of charge is the product of the number of elementary charges (electrons or protons) and the magnitude of the elementary charge.

$$q = Ne$$

Quantity	Symbol	SI unit
amount of charge	q	C (coulomb)
number of elementary charges	N	integer (pure number, no unit)
elementary charge	e	C (coulomb)

MODEL PROBLEM

Charge and Electrons

A light bulb draws a current of 0.60 A. If the bulb is left on for 8.0 min, how many electrons (elementary charges) pass through the bulb?

Frame the Problem

- When a *current* exists in a light bulb, *electrons* are passing through it.
- If you know the amount of charge that passes through the light bulb, you can use the magnitude of the *elementary charge* to find the number of electrons.

Identify the Goal

The number, N, of electrons passing through the bulb

Variables and Constants

Known	Implied	Unknown
$I = 0.60\ \text{A}$	$e = 1.60 \times 10^{-19}\ \text{C}$	q
$\Delta t = 8.0\ \text{min}$		N

Strategy

Use the definition of current to find the amount of charge passing through the light bulb in 8.0 min.

Calculations

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

First, convert time to SI units.

$$8.0\ \cancel{\text{min}}\ \frac{60\ \text{s}}{\cancel{\text{min}}} = 480\ \text{s}$$

Substitute first

$$0.60\ \text{A} = \frac{q}{480\ \text{s}}$$

$$(0.60\ \text{A})(480\ \text{s}) = \frac{q}{\cancel{480\ \text{s}}}\cancel{480\ \text{s}}$$

1 A · s is equivalent to 1 C.

$$q = 288\ \text{A} \cdot \text{s}$$

$$q = 288\ \text{C}$$

Solve for *Q* first

$$(I)(\Delta t) = \frac{q}{\cancel{\Delta t}}\cancel{\Delta t}$$

$$q = (0.60\ \text{A})(480\ \text{s})$$

$$q = 288\ \text{A} \cdot \text{s}$$

$$q = 288\ \text{C}$$

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Strategy

Use the relationship between amount of charge and the elementary charge to find the number of electrons.

Calculations

$$q = Ne$$

Substitute first

$$288\ \text{C} = N\ 1.60 \times 10^{-19}\ \text{C}$$

$$\frac{288\ \cancel{\text{C}}}{1.60 \times 10^{-19}\ \cancel{\text{C}}} = \frac{N\ \cancel{1.60 \times 10^{-19}\ \text{C}}}{\cancel{1.60 \times 10^{-19}}\ \text{C}}$$

$$N = 1.80 \times 10^{21}$$

Solve for *N* first

$$\frac{q}{e} = \frac{N\cancel{e}}{\cancel{e}}$$

$$N = \frac{288\ \cancel{\text{C}}}{1.60 \times 10^{-19}\ \cancel{\text{C}}}$$

$$N = 1.80 \times 10^{21}$$

In the 8.0 min that the light bulb was on, 1.8×10^{21} electrons (elementary charges) passed through it.

Validate

In the first part, the units combine to give coulombs, which is correct for charge. In the second part, the units cancel to give a pure number. This is correct, because there are no units for number of electrons. The answer is extremely large, which you would expect because the number of electrons in one coulomb is exceedingly large: $N = \frac{1\ \cancel{\text{C}}}{1.60 \times 10^{-19}\ \cancel{\text{C}}}$ or 6.25×10^{18} electrons.

PRACTICE PROBLEMS

12. Calculate the current if 2.85×10^{20} elementary charges pass a point in a circuit in 5.70 min.

13. A 16.0 V battery does 5.40×10^{4} J of work in 360.0 s.

- **(a)** Calculate the current through the battery.
- **(b)** Calculate the number of elementary charges that pass through the battery.

14. Calculate the number of elementary charges that pass a point in a circuit when a current of 3.50 A flows for 24.0 s.

15. In transferring 2.5×10^{20} elementary charges in 12 s, a battery does 68 J of work.

- **(a)** Calculate the current through the battery.
- **(b)** Calculate the potential difference of the battery.

Electric Circuits

Suppose a power supply (battery) is connected to a load such as a light bulb. A switch allows you to open and close the circuit. An **open circuit** means there is a break (perhaps an open switch) somewhere in the circuit that prevents current from flowing. A **closed circuit** means that all connections are complete. A closed, or continuous, path exists, allowing current to move around the circuit. You could represent the above circuit by using realistic drawings of the apparatus involved, as shown in Figure 15.10. That technique would be very cumbersome, however. It is much more efficient to represent and analyze electric circuits by using the electric-circuit symbols shown in Figure 15.11. The circuit shown in Figure 15.10 is redrawn in Figure 15.12, using these symbols.

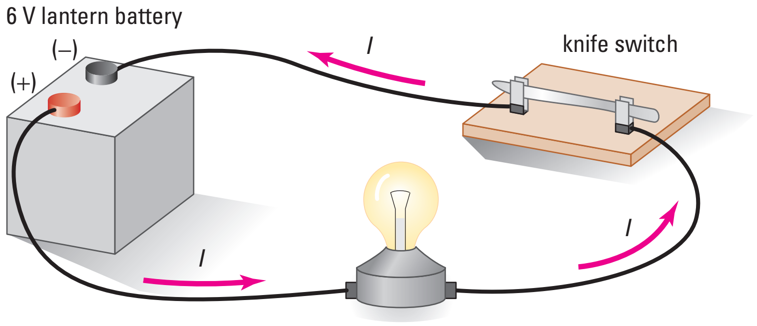


Figure 15.10 A realistic sketch of even a simple circuit is cumbersome.

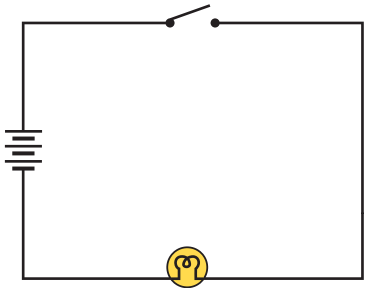


Figure 15.12 This diagram of the same circuit is easier to draw and to analyze.

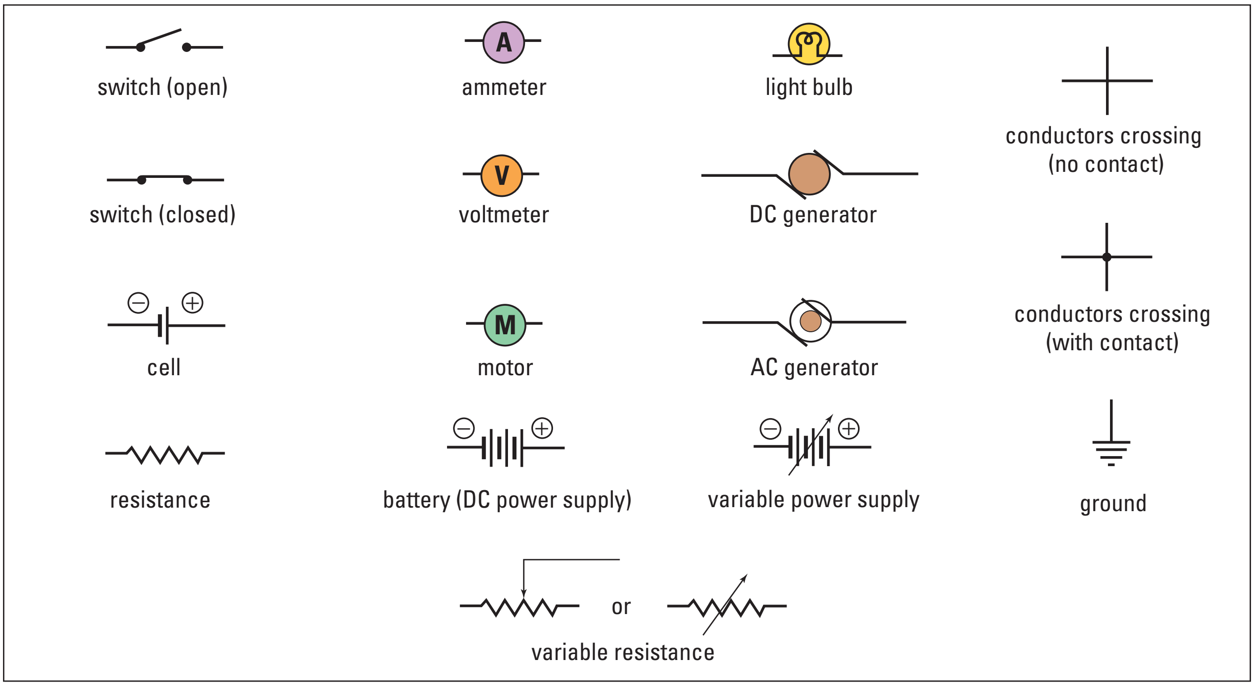
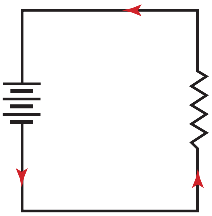


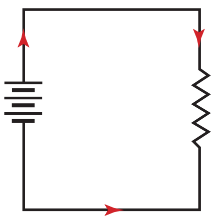
Figure 15.11 Symbols for elements of an electric circuit

Conceptual Problems

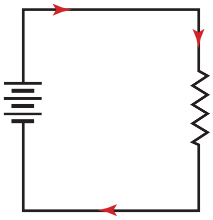
- In the circuit symbol for a battery, the longer line represents the positive pole of the battery and the shorter line is the negative pole. In one of the circuits shown here, the arrows represent conventional current. In another, the arrows represent electron flow. One circuit is drawn incorrectly. Neither conventional current nor electron flow could take the directions indicated by the arrows. Analyze the circuits and determine which illustrates conventional current, electron flow, and neither. Explain your reasoning.



(a)

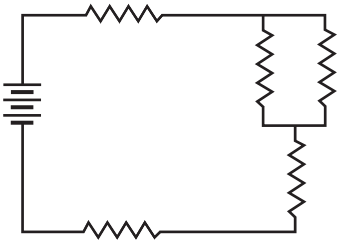


(b)



(c)

- Copy the circuit at the right in your notebook. Add arrows to every branch of the circuit, showing the direction of conventional current.



Ammeters and Voltmeters

To find out what is happening inside the parts of a circuit, scientists use an assortment of devices, such as ammeters, voltmeters, galvanometers, and ohmmeters. A simple circuit is composed of **loads** (for example, light bulbs, resistances, motors) and a **power supply** (cell, battery, or an AC or DC generator). These **circuit elements** (loads and power source) may be connected in series or in parallel to each other. A switch is often included but serves only to open or close the circuit. When meters are used to measure current or potential difference, they are connected in a way that will not interfere with the circuit operation. An **ammeter** measures the electric current to or from a circuit element. A **voltmeter** measures the electric potential difference across a circuit element.

Since ammeters measure the current through a circuit element, they must be inserted into the line before or after the circuit element so that all of the current passing through the circuit element also goes through the ammeter. This is called a **series** connection since the current moves through the circuit element and the ammeter one after the other. On the other hand, a voltmeter measures the potential difference from one side of a circuit element to the other. To function properly, voltmeters must be connected to the opposite sides of the circuit element across which you want to know the potential difference. This is a called a **parallel** connection, since the voltmeter presents a path that runs beside the circuit element. Notice that the ammeter is actually part of the circuit. If you disconnect either pole of the ammeter, the circuit is opened. The voltmeter, on the other hand, makes contact with the circuit at two points to measure the potential difference between those points. If you disconnect either pole of the voltmeter, the circuit is still perfectly functional. Figure 15.13 shows the same circuit as in Figure 15.10, with the addition of an ammeter and a voltmeter showing the proper connection.

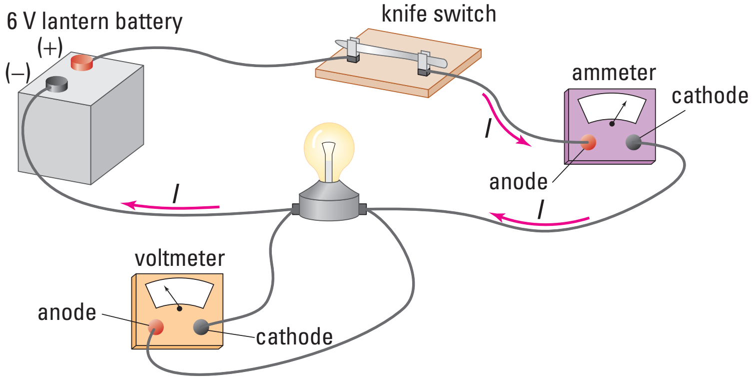


Figure 15.13 Notice the labels indicating the anodes and cathodes of the meters relative to the anode and cathode of the power supply and the direction of the current. How would you connect a voltmeter to measure the potential difference of the battery?

15.2 Section Review

1. **K/U** How is the SI unit of charge, the coulomb, related to the elementary charge?
2. **K/U** Give an example of a current in which positive charges move.
3. **C** When Millikan measured the amount of charge on oil drops, he obtained data similar to the following. Explain how he used such data to determine (a) that elementary charges existed, and (b) the size of the elementary charge.

   Data: 6.4×10^{-19} C, 1.28×10^{-18} C, 1.92×10^{-18} C, 8.0×10^{-19} C, 1.6×10^{-18} C, 6.4×10^{-19} C, 1.12×10^{-18} C.
4. **C** Explain how a voltmeter must be connected in a circuit in order to measure the potential difference across a light bulb.