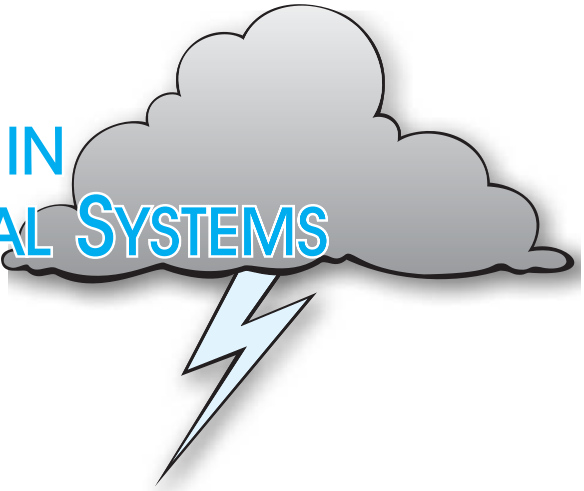
1.3 Voltage in Electrical Systems



Objectives

- Explain the similarities and differences between Newton's law of universal gravitation and Coulomb's law.
- Explain how the force between two like charges and the force between two unlike charges are different.
- Describe how to create an electric field. Interpret the information given in a drawing of an electric field.
- Define electric potential difference, or voltage.
- Differentiate between AC and DC.
- Identify the most common source of DC voltage.
- Describe how to connect DC voltage sources so that voltages will add.

INTERNET *connection*

To find out more about voltage in electrical systems, follow the links at **www.learningincontext.com**.

Gravitational force and electrical force are two *universal forces* in nature. They are called *universal* because each force acts the same everywhere in the observable universe. Gravitational forces act between two or more masses; electrical forces act between two or more charges. Although they are not the same kinds of forces, gravitational and electrical forces are alike in many ways. For example, they are both forces acting at a distance. The Earth exerts a gravitational force on the moon even though the two bodies do not touch.

In this section you will learn about electric force, electric fields, and electric potential, or voltage. But first, we introduce force acting at a distance with gravity, since you have experience with gravitational forces.

Gravitational Force

In the 17th century, Newton developed the theory of gravitational force by analyzing the motion of the planets about the sun. The orbits of the planets are approximately circular. Without a force acting on the planets, they would travel off, away from the solar system, in straight lines. Newton proposed that an inward gravitational force is exerted on each planet that causes the planet to travel in a circle about the sun. This force is the same kind of force exerted on an apple that causes the apple to fall toward the center of the Earth when it drops from a tree.

Newton's analysis showed that the source of the gravitational force causing planetary orbits is the sun. He deduced that this force varies with distance in a special way—the force decreases with the square of the distance between the sun and the planet. For example, a planet twice as far from the sun as the Earth would be pulled toward the sun with $1/4$ the force; a planet 3 times as far from the sun would be pulled with $1/9$ the force; and so on. This type of relationship is called an inverse square law. **Newton's universal law of gravitation** is:

> *Every object in the universe attracts every other object with a force that (for two bodies) is directly proportional to the mass of each body and that is inversely proportional to the square of the distance between them.*

Mathematically, the law can be written as

$$F_g = G\frac{m_1 m_2}{d^2}$$

where m_1 and m_2 are the masses of two objects and d is the distance between them. (See Figure 1.29 on the next page.) The quantity G is called the universal gravitational constant, and its value is

$$G = 6.67 \times 10^{-11} \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}$$

The gravitational force F_g is exerted equally on both masses m_1 and m_2. But the direction of the force is different for the two masses. The force on m_1 is directed toward m_2, and the direction of the force on m_2 is toward m_1. In other words, the gravitational force is always an attractive force.

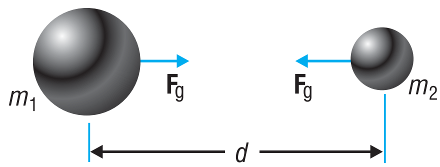


Figure 1.29
The gravitational forces between two spherical masses

Example 1.11 Force of Gravity Between Earth and Moon

The mass of the Earth is 5.98×10^{24} kg, and the mass of the moon is 7.36×10^{22} kg. The average separation distance between the Earth and moon is 3.85×10^{5} km. What force does the Earth exert on the moon to keep the moon in orbit?

Solution: $F_g = G\dfrac{m_1 m_2}{d^2}$

$$= 6.67 \times 10^{-11} \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2} \cdot \frac{(5.98 \times 10^{24}\ \text{kg})(7.36 \times 10^{22}\ \text{kg})}{(3.85 \times 10^{8}\ \text{m})^2}$$

$$= 1.98 \times 10^{20}\ \text{N}$$

The Earth exerts a force of 1.98×10^{20} N on the moon.

Electric Charge

Have you ever run a comb through your hair on a dry day and seen how the comb can pick up small pieces of lint or paper? Why does a television screen or computer monitor attract dust after being on for a period of time? These forces of attraction cannot be due to gravity, because the gravitational forces would be far too small. They are due to electrical forces. Electrical forces have been studied for centuries. In fact, the word *electrical* comes from the Greek *elektron*, which means amber, the substance used by the ancient Greeks to study electrical forces.

The property of an object that causes electrical force is called **charge**. A great number of experiments on many different materials have shown that electrical forces can be attractive or repulsive. Thus, there must be two types of electric charge. They have been named positive charge and negative charge. If two objects have the same charge, both positive or both negative, they repel. If two objects have opposite charges, one positive and the other negative, they attract. (See Figure 1.30 on the next page.)

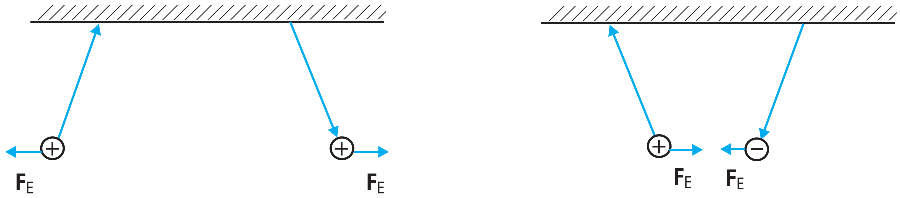


Figure 1.30
Like charges repel. Unlike charges attract.

The origin of electric charge is found in the atom. The nucleus of the atom contains most of the mass, in the neutrons and protons. Neutrons have no charge (they are *neutral*), while protons have a positive charge. The nucleus is surrounded by a group, or cloud, of electrons. Electrons have a negative charge. The mass of an electron is about 1/2000 of the mass of a proton or neutron. But the charge of an electron is exactly equal to the charge of a proton, and of opposite sign. The force of attraction between protons and electrons is what keeps the electrons bound to the nucleus.

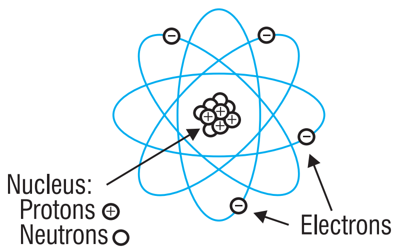


Figure 1.31
A simple model of the atom, showing its major parts

A normal atom has no net charge—it has equal numbers of protons and electrons and is electrically neutral. The net charge in a system is the algebraic sum of the charges present, or the number of positive charges minus the number of negative charges. The net charge can be positive, negative, or zero (neutral).

You can transfer charge from one object to another because the outermost electrons in the atoms of some substances are not tightly bound to the nucleus, and can be removed. When you run a comb through your hair, friction transfers electrons from your hair to the comb. The comb now has more electrons than protons, and becomes negatively charged. Your hair has fewer electrons than protons, and becomes positively charged.

In this example, you move electrons from one place to another, but you do not create or destroy charge. You can consider your hair and the comb an isolated system. In an isolated system, particles and charge cannot enter or leave the system.

The net electric charge in an isolated system never changes.

This is the **principle of conservation of charge**. Every known physical process conserves electric charge.

Electrical Force

In the 18th century, the French scientist Charles Coulomb made intricate measurements on charged spheres. He discovered a relationship between force, charge, and distance. This relationship is now called **Coulomb's law**:

> *The electrical force between two charged bodies is directly proportional to the charge on each body and inversely proportional to the square of the distance between them.*

Mathematically, the law can be written as

$$F_E = K\frac{q_1 q_2}{d^2}$$

where q_1 and q_2 are the charges on two objects, d is the distance between them, and K is a constant. The SI unit for charge is the **coulomb** (C). The charge on one electron or proton is 1.60×10^{-19} C. This is called the **elementary charge**. When q_1 and q_2 are measured in coulombs, distance is measured in meters, and force is measured in newtons, the constant K has the value

$$K = 9.0 \times 10^9 \ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}$$

Compare Coulomb's law to Newton's law of universal gravitation. They are both inverse square laws. They both give the magnitude of the force one object exerts on another, which is also the force the second object exerts on the first. In Newton's law, mass m_1 exerts a force on m_2 and mass m_2 exerts the same magnitude force on m_1. In Coulomb's law, charge q_1 exerts a force on q_2 and charge q_2 exerts the same magnitude force on q_1. But, gravitational force is always attractive (there is only one kind of mass), whereas electrical force can be attractive or repulsive (there are two kinds of charge).

The directions of electrical forces are as shown in Figure 1.32. In both cases, the forces act along a line through the centers of the charges. If q_1 and q_2 have the same sign, the force on q_1 acts away from q_2 and the force on q_2 acts away from q_1. If q_1 and q_2 have opposite signs, the force on q_1 acts toward q_2 and the force on q_2 acts toward q_1.

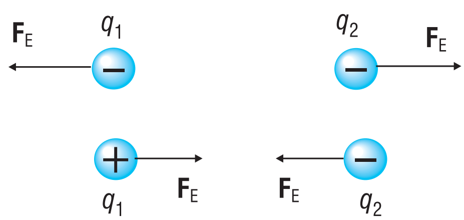


Figure 1.32
To determine the direction of electrical force, remember that like charges repel and unlike charges attract.

Example 1.12 Electrical and Gravitational Forces in the Hydrogen Atom

An electron has a mass of approximately 9.1×10^{-31} kg, and a proton has a mass of approximately 1.7×10^{-27} kg. In a hydrogen atom, the electron and proton are separated by an average of 5.3×10^{-11} m. Compare the electrical force of attraction between the electron and proton to the gravitational force of attraction.

Solution:

$$F_E = K\frac{q_1 q_2}{d^2}$$

$$= 9.0 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\text{C}^2} \cdot \frac{(1.6 \times 10^{-19}\text{ C})(1.6 \times 10^{-19}\text{ C})}{(5.3 \times 10^{-11}\text{m})^2}$$

$$= 8.2 \times 10^{-8}\text{ N}$$

$$F_g = G\frac{m_1 m_2}{d^2}$$

$$= 6.67 \times 10^{-11} \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2} \cdot \frac{(9.1 \times 10^{-31}\text{ kg})(1.7 \times 10^{-27}\text{ kg})}{(5.3 \times 10^{-11}\text{m})^2}$$

$$= 3.7 \times 10^{-47}\text{ N}$$

The ratio of electrical force to gravitational force is

$$\frac{F_E}{F_g} = \frac{8.2 \times 10^{-8}\text{ N}}{3.7 \times 10^{-47}\text{ N}} = 2.2 \times 10^{39}$$

The electrical force is over 10^{39} greater than the gravitational force.

On a small scale, with distances and masses as small as the atom, electrical forces are important and gravitational forces are insignificant. On a larger scale, with distances and masses as large as the moon, Earth, and sun, gravitational forces are important and electrical forces are insignificant. Gravitational forces govern the structure of planets, stars, and galaxies. Electrical forces govern the structure of atoms, molecules, solids, liquids, and gases.

Gravitational and Electric Fields

Both gravitational forces and electrical forces can act over distance. You can think of the space around a mass like the Earth as being altered in some way, such that another mass like a satellite feels a force. Similarly, the space around a proton is altered such that an electron feels a force. These "alterations of space" are called gravitational fields and electric fields. The satellite is thought of as interacting with the gravitational field created by the earth, and the electron is thought of as interacting with the electric field created by the proton.

A field is an imaginary construction used by scientists, engineers, and technicians to help them understand and predict how forces are transmitted from one object to another. For example, imagine placing a "test" mass *m* at a certain point in the gravitational field of the Earth. The test mass feels a force directed toward the center of the Earth, whose magnitude is given by:

$$F_g = G\frac{m_E m}{d^2}$$

where m_E is the mass of the Earth. The gravitational field is represented by the following equation.

$$\mathbf{g} = \frac{\mathbf{F_g}}{m}$$

Since force is a vector, the field is a vector. The direction of **g** is the direction of the force on the test mass. You can move the test mass around, and at every point measure or calculate a different value of **g**. Thus, at every point in space around the Earth, the gravitational field can be represented by a vector of length *g* pointing toward the center of the Earth. Notice that, if you substitute the expression for F_g, the *m* in the numerator cancels the *m* in the denominator. Therefore, **g** does not depend on the size of the test mass.

Now imagine placing a positive test charge *q* at a certain point in the electric field of a proton. The test charge feels a force directed away from the center of the proton, whose magnitude is given by:

$$F_E = K\frac{q_p q}{d^2}$$

where q_p is the charge of the proton. The electric field is represented by the following equation.

$$\mathbf{E} = \frac{\mathbf{F}_E}{q}$$

The electric field is also a vector. The direction of **E** is the direction of the force on the positive test charge. You can move the test charge around, and measure or calculate a different value of **E** at every point. Thus, at every point in space around the proton, the electric field can be represented by a vector of length *E* pointing away from the center of the proton. If you substitute the expression for F_E, the *q* in the numerator cancels the *q* in the denominator. Therefore, **E** does not depend on the size of the test charge.

One way to visualize a field is with a diagram showing arrows at various locations to represent field vectors. The length of each arrow shows the strength of the field. The direction of the arrow shows the field direction.

Alternatively, fields are illustrated by drawing **field lines**. Field lines for five electric fields are shown in Figure 1.33. The direction of a field at any point is tangent to the field line at that point. Where the lines are close together, the magnitude of the field is high; where the lines are far apart, the magnitude of the field is low. Notice that a field diagram can show only some of the infinite number of possible lines. The field lines in Figure 1.33 are shown in only two dimensions, but the electric field is three dimensional.

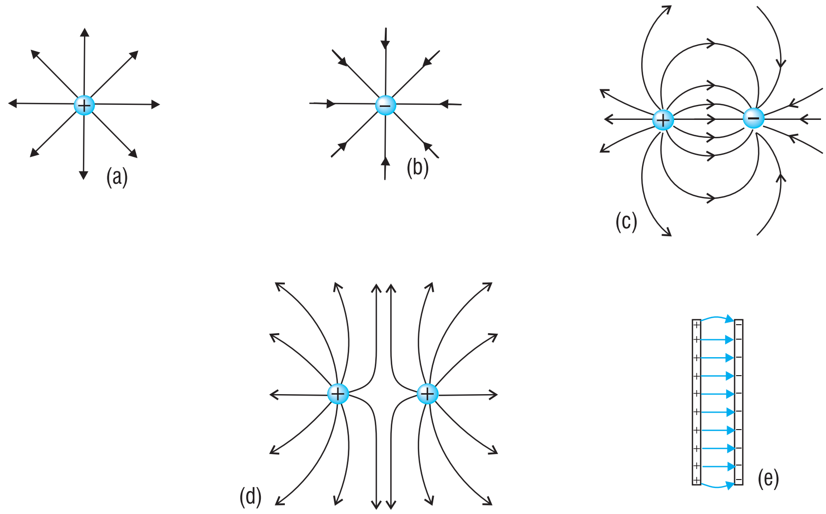


Figure 1.33
Electric field configurations, showing electric field lines for: (a) a single positive charge, (b) a single negative charge, (c) a pair of equal, opposite charges, (d) a pair of equal charges with the same sign, and (e) two oppositely charged parallel plates

Electric Potential

When you lift a book off a table, you move the book through the Earth's gravitational field. You must exert a force against the force of gravity to move the book a certain distance. We say the book possesses a **potential** at this distance above the table because, if you release the book, it will accelerate and fall back to the tabletop.

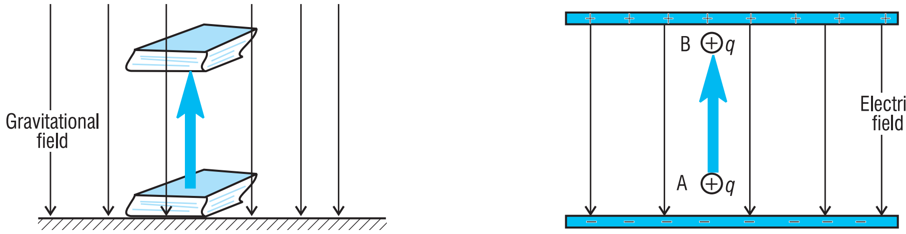


Figure 1.34
A mass has potential if it is moved through a gravitational field.
A charge has potential if it is moved through an electric field.

Similarly, if you move a charge against an electric field, you must exert a force on the charge. Suppose you move a charge a distance d from A to B in a uniform electric field, as shown in Figure 1.34. The charge possesses a potential at B because, if you release it, the charge will accelerate back toward A. We say the field creates an **electric potential difference** between A and B. In a uniform electric field of magnitude E, the electric potential difference ΔV_{AB} between two points A and B, separated by a distance d is the following product

$$\Delta V_{AB} = E \times d$$

The unit of measurement for electric potential difference is the **volt**. Electric potential difference is sometimes simply called **electric potential**, and also **voltage**.

Voltage is the prime mover in electrical systems, like pressure is the prime mover in fluid systems. Consider the simple fluid and electrical systems shown in Figure 1.35. In the fluid system, the water heights in the connected reservoirs are different. The Earth's gravitational field causes a pressure difference, which results in water flow from the left to the right reservoir. The flow will stop when the water levels are equal and there is no longer a pressure difference.

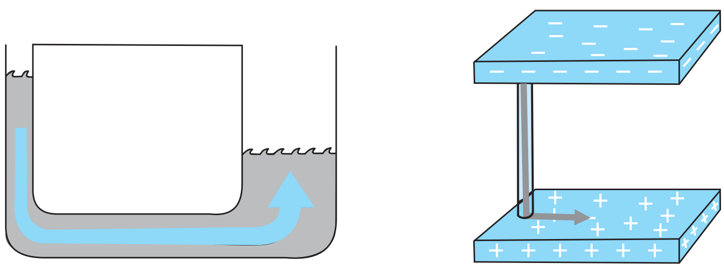


Figure 1.35
Pressure difference is the prime mover in a fluid system.
Potential difference is the prime mover in an electrical system.

In the electrical system, charge has been separated on parallel plates, and the plates are then connected. The electric field causes a potential difference, or voltage, which results in charge flow from the top to the bottom plate. A flow of charge is called an electric **current**. The current will stop when the plates are electrically neutral and there is no longer a potential difference.

In the fluid system, flow can be maintained with a pump. The pump is a source of pressure difference. In the electrical system, current can be maintained with a battery. A battery is a source of potential difference. A source of potential difference is also called a voltage source.

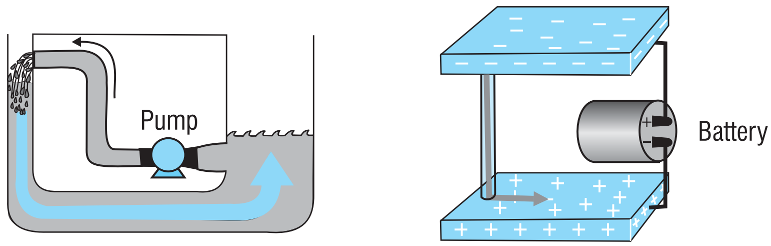


Figure 1.36
A pump is a source of pressure difference.
A battery is a source of potential difference.

Components of Electrical Systems

Electrical systems usually contain four major components:

- at least one voltage source, usually a battery or generator;
- conductors, which can be metal wire or metal connections on printed circuits;
- at least one load; and
- one or more control elements, such as switches.

Figure 1.37 shows how the components are connected in a generalized electrical system.

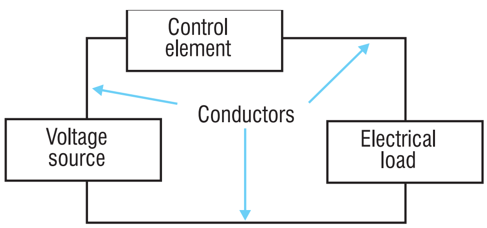


Figure 1.37
Components of a generalized electrical system

The **load** in an electrical system is usually an appliance or machine, such as an electric motor, water heater, lights, television set, computer, or air conditioner. The purpose of an electrical system like the one shown above is to provide voltage and current to the load. An electrical **conductor** is a material through which charge can easily flow. The **control element** can be a switch that turns the current in the system on or off, or a variable control switch such as the volume control on a stereo.

An **electrical circuit** is a closed path for current flow created by connecting voltage sources, conductors, control elements, and loads.

Direct Current and Alternating Current

There are two types of current used in electrical circuits: **direct current** (DC) and **alternating current** (AC). In DC, the electric charge flows in one direction. In AC, charge flows back and forth, rapidly changing direction many times each second. Whether a circuit uses AC or DC depends on the type of voltage source. For example, batteries produce DC voltage, and alternators produce AC voltage.

Batteries Are Typical DC Voltage Sources

The most common type of DC voltage source is a battery. Batteries are used in portable electric devices, such as cellular phones, flashlights, laptop computers, watches, cars, boats, cameras, and toys. The terms *battery* and *cell* are often used interchangeably, but they have different meanings. A cell is a single unit that houses one or more chemicals. As the chemicals react, electrons are removed from certain molecules, leaving behind positively charged ions. The electrons and ions are separated, and this charge separation creates a voltage. A battery is a bank or collection of two or more cells connected together.

The voltage produced by a cell's chemical reaction depends on the materials used in the reaction. These materials differ among various battery technologies. For example, a standard D cell used for flashlight batteries uses an alkaline reaction and has a cell voltage of 1.5 volts. Most car batteries have six lead-acid cells, each with a cell voltage of 2.0 volts, yielding a 12-volt battery.

The voltage of a cell drops over the course of its life, as the chemical reaction that produces the voltage slows down. When the voltage drops below the requirement for the device it is being used for, the battery is "dead." If it cannot be recharged, a dead battery must be replaced with a new one. *Primary cells* are those designed for one-time use. *Secondary cells* can be recharged. Recharging is usually cheaper and more convenient than replacement. In addition, the chemicals in cells can be toxic to the environment, making rechargeability even more important.

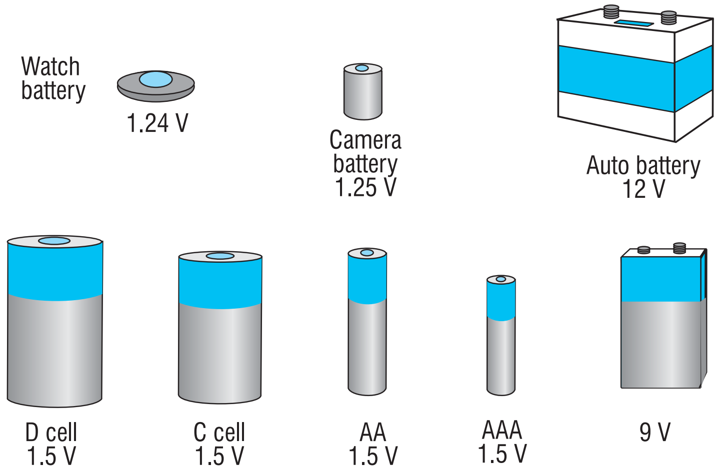


Figure 1.38
Typical voltage sources

In a typical recharging process, current is sent through the battery in a reverse direction. This reverses the direction of the chemical reaction and makes the material available again to produce voltage. Table 1.6 lists the voltage and chemically active materials in typical primary and secondary cells.

Table 1.6 Types of Primary and Secondary Cells for Batteries

Primary (One-Time Use)		Secondary (Rechargeable)	
Cell Voltage	**Chemistry**	**Cell Voltage**	**Chemistry**
1.5	Carbon-Zinc	2.0	Lead-Acid
1.5	Alkaline	1.2	Nickel-Cadmium
1.3	Mercury	1.2	Nickel Metal Hydride
1.6	Silver Oxide	3.6	Lithium Ion
3.0	Lithium	3.0	Lithium Metal
1.4	Zinc-Air		

Connecting Cells to Add Their Voltages

The voltage output of a cell or battery is measured between two terminals that are located on the housing. These terminals are called **electrodes**. Electrodes on car batteries are metal posts on the top or side of the housing. On other batteries, such as those used in flashlights and cellular phones, electrodes are located at opposite ends of the cylindrical housing.

One electrode is marked **positive** (+) and the other **negative** (–). Sometimes they're just color-coded, with red for positive (+) and black for negative (–). When batteries are connected in a circuit, electrons move in the circuit as if they were flowing out of the negative electrode, through the circuit, and into the positive electrode. The negative electrode is called the **cathode**. The positive electrode is called the **anode**.

Most electrical devices require several volts (at least) from the batteries for the devices to operate. This means that two or more cells must be combined so that their voltages add. Cells can be added together in **series** to produce a higher voltage. Adding cells in series means that the positive terminal from one cell is connected to the negative terminal of another cell, as shown in Figure 1.39. When this is done, the electrons from each cell will flow in the same direction. The voltages of the individual cells add together to give a higher total voltage.

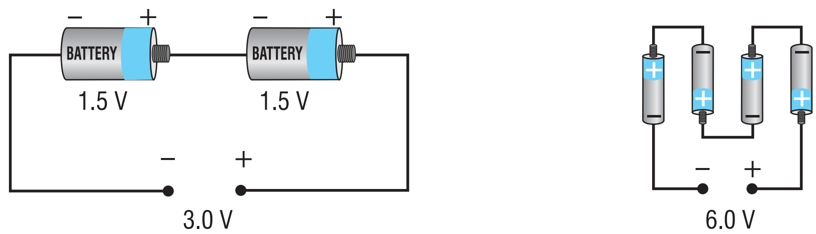
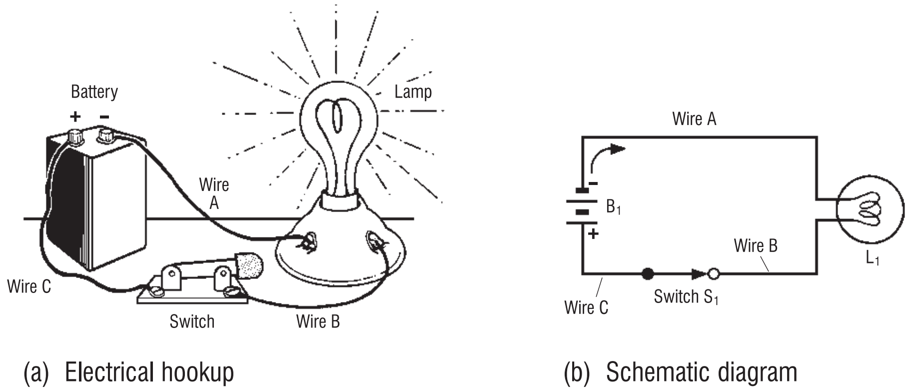


Figure 1.39
Connecting DC voltage sources in series results in the addition of voltages.

A Simple DC Circuit

Figure 1.40 shows a simple circuit. The components are shown in Figure 1.40a: a battery, a switch, three wires, and a lamp. The battery is the voltage source. The light bulb is the load. The wires (and lamp base) are the conductors. Electrons flow from the negative battery terminal (cathode) through wire A into the lamp base. Electrons then flow through the filament of the light bulb and back into the lamp base, through wire B, a switch, and wire C, and into the positive terminal of the battery (anode). Figure 1.40b shows a schematic diagram of this simple circuit. A schematic diagram acts like a road map for you to easily identify the current path and the components of the circuit.

Shorthand symbols are used to indicate the components. In this circuit, four symbols are shown: the battery, (—|I|—), the light bulb ( ), the switch (—•—•○—) and the conductors (———).



(a) Electrical hookup

(b) Schematic diagram

Figure 1.40
A simple DC circuit

AC Circuits

An AC voltage source reverses the positive and negative terminals many times per second. The current in these circuits flows in one direction, then in the opposite direction, changing in response to the changing voltage source. The overwhelming majority of AC circuits involve voltages and currents that alternate, or cycle, at a rate of 60 times each second. The cycling rate is called the **frequency**. Frequency is measured in cycles per second, or **hertz**.

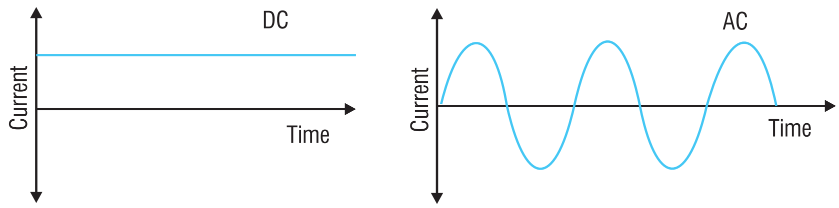


Figure 1.41
The current-time relationships for DC and AC

The main source of 60-hertz current comes from electrical power-generating plants. AC electricity is carried over great distances from power plants to homes and factories in overhead or underground high-voltage lines. The voltage in residential homes that's available at the electrical wall sockets is usually 110 to 120 volts. However, outlets for air-conditioners or clothes dryers may be 220 to 240 volts. These loads require higher voltage and current because they dissipate more power than other household appliances. You will learn about power, and its relationship to voltage and current in Chapter 6.

Summary

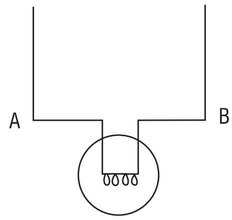
- Newton's law of universal gravitation and Coulomb's law are both inverse square laws. The magnitudes of both forces decreases with the square of the distance between the masses and the charges.
- Atoms are composed of protons, neutrons, and electrons. Protons are positively charged, electrons are negatively charged, and neutrons have no charge.
- The flow of electrons in an electrical system is a current.
- Unlike charges attract; like charges repel.
- An electric field is a model of the alteration of space around one or more charges. You can use the field to predict the force exerted on a charge placed in the field.
- The potential difference, or voltage, between two points in a uniform electric field is the product of the field strength and the distance between the points.
- Voltage is the prime mover in electrical systems.
- A battery is a source of DC voltage. It can maintain a current in an electrical circuit.
- Batteries or cells can be connected in series to increase voltage.

Exercises

1. Planets revolve around stars because of gravity. However, gravity is not restricted to acting only between large and small bodies—stars can also revolve around other stars. Two stars revolving around each other form a binary star system. In a binary star system, by how much does the gravitational force between the stars decrease when the distance between them triples? Increases tenfold?
2. Describe two ways in which gravitational forces are like electrical forces.
3. Describe one major difference between gravitational forces and electrical forces.
4. Gravitational and electrical forces act over distances. In other words, two bodies can exert force on each other even if they do not touch. Which force is greater over the distance between the Earth and the sun? Which force is greater over the distance between two oxygen atoms in a water molecule?

5. An astronaut having a mass of 65 kg is standing on the surface of the moon. The mass of the moon is 7.36×10^{22} kg and the radius is 1.74×10^{6} m. What is the gravitational force the astronaut exerts on the moon?

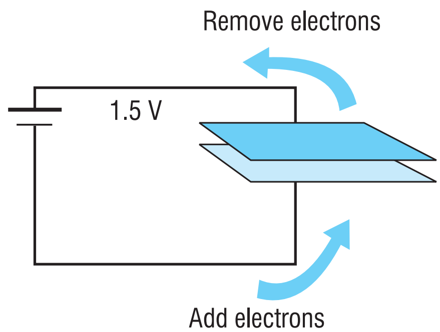
6. When you walk across a carpet, you scuff electrons from your shoes onto the carpet. Are your shoes then positively or negatively charged? Is the carpet positively or negatively charged? What happens when you touch a doorknob?



7. A lamp is connected to an electric circuit between A and B. When the circuit is complete, electrons flow through the lamp. What can you say about the electric potentials at A and B?

8. Voltage in electric circuits is similar to pressure in fluid circuits. A pressure difference between two points in a complete fluid circuit will make fluids move. A voltage difference between two points in a complete electric circuit will make _____________ move.

9. Two metal plates placed parallel to each other with air between them form a device called a capacitor. When the plates are connected in a circuit with a battery as shown, the battery voltage causes some electrons to move away from the top plate and causes some other electrons to move onto the bottom plate.



If 5×10^{12} electrons are removed from the top plate and added to the bottom plate, what is the unbalanced charge, in coulombs, on each plate? (Remember, the elementary charge is 1.60×10^{-19} C.)

10. When the 1.5-volt battery charges the capacitor in Exercise 9, the electric field between the plates of the capacitor is approximately uniform and equal in magnitude to $1800 \ \frac{\text{V}}{\text{m}}$. What is the separation distance between the plates?

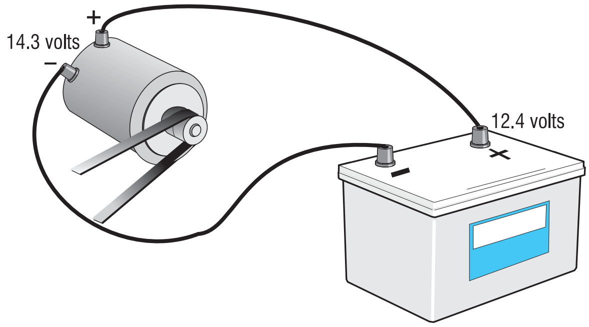
11. The distance between the plates of the capacitor in Exercise 9 is 0.1 mm. Find the magnitude of the electric field between the plates.

12. The value of the charge of an electron or proton has been determined to an accuracy of 2.9 parts per million. The result is $1.6021892 \times 10^{-19}$ coulombs. Why would it be impossible for one plate of a capacitor, such as shown in Exercise 9, to have a charge of 4.0856×10^{-18} coulombs?

13. The output voltage of an automobile battery is measured to be 12.4 volts before it is connected in the circuit shown below. After the battery is connected, the alternator has an output voltage of 14.3 volts.

    (a) What is the net voltage available to produce current in the circuit?

    (b) Which voltage source, the battery or alternator, is forcing current to flow in the circuit?



14. When electrical current moves in only one direction through an electrical circuit it is called ________________ current.

15. Electrical current that continuously changes direction is called ________________ current.

16. What is a common source of direct current? What is a common source of alternating current?

17. When you use such terms as “frequency,” “Hertz,” or “cycles/second” to describe electrical current you are describing ___________________ current.

18. Find the unknown voltage in each of these circuits.