15 Electrostatics

15-1 Electrostatic Force

Vocabulary **Electrostatics:** The study of electric charges, forces, and fields.

The symbol for electric charge is the letter "q" and the SI unit for charge is the **coulomb (C).** The coulumb is a very large unit.

1 C = 6.25×10^{18} electrons or
1 electron has a charge of 1.60×10^{-19} C.

Electrons surrounding the nucleus of an atom carry a negative charge. Protons, found inside the nucleus of the atom, carry a positive charge of 1.60×10^{-19} C, while neutrons (which also reside in the nucleus) are neutral. It is important to remember that only electrons are free to move in a substance. Protons and neutrons usually do not move.

When two objects with like charges, positive or negative, are brought near each other, they experience a repulsive force. When objects with opposite charges, one negative and one positive, are brought side by side, they experience an attractive force. These forces can be described with Coulomb's law.

Vocabulary **Coulomb's Law:** Two charged objects attract each other with a force that is proportional to the charge on the objects and inversely proportional to the square of the distance between them.

$$F \propto \frac{q_1 q_2}{d^2}$$

This equation looks very similar to Newton's law of universal gravitation. As before, the sign $\propto$ means "proportional to." To make an equation out of this proportionality, insert a quantity called the **electrostatic constant, *k*.**

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

The magnitude of Coulomb's law can now be written as an equation.

$$\textbf{electrostatic force} = \frac{\textbf{(electrostatic constant)(charge 1)(charge 2)}}{\textbf{(distance)}^2} \quad \text{or} \quad F = \frac{kq_1q_2}{d^2}$$

Like all other forces, the electrostatic force between two charged objects is measured in newtons.

Solved Examples

Example 1: Anthea rubs two latex balloons against her hair, causing the balloons to become charged negatively with 2.0×10^{-6} C. She holds them a distance of 0.70 m apart. a) What is the electric force between the two balloons? b) Is it one of attraction or repulsion?

Solution: It is not necessary to carry the sign of the charge throughout the entire exercise. However, when determining the direction of your final answer, it is important to remember the charge on each object.

Given: $q_1 = 2.0 \times 10^{-6}\ \text{C}$
$q_2 = 2.0 \times 10^{-6}\ \text{C}$
$d = 0.70\ \text{m}$
$k = 9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$

Unknown: $F = ?$
Original equation: $F = \dfrac{kq_1q_2}{d^2}$

$$\textit{Solve: } F = \frac{kq_1q_2}{d^2} = \frac{(9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2)(2.0 \times 10^{-6}\ \text{C})(2.0 \times 10^{-6}\ \text{C})}{(0.70\ \text{m})^2} = \mathbf{0.073\ N}$$

b) Because both balloons are negatively charged, they will repel each other.

Example 2: Two pieces of puffed rice become equally charged as they are poured out of the box and into Kirk's cereal bowl. If the force between the puffed rice pieces is 4×10^{-23} N when the pieces are 0.03 m apart, what is the charge on each of the pieces?

Solution: Because both charges are the same, solve for both q's together. Then find the square root of that value to determine one of the charges.

Given: $F = 4 \times 10^{-23}\ \text{N}$
$d = 0.03\ \text{m}$
$k = 9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$

Unknown: $q = ?$
Original equation: $F = \dfrac{kq_1q_2}{d^2}$

$$\textit{Solve: } q_1q_2 = \frac{Fd^2}{k} = \frac{(4 \times 10^{-23}\ \text{N})(0.03\ \text{m})^2}{9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2} = 4 \times 10^{-36}\ \text{C}^2$$

This is the square of the charge on the pieces of puffed rice. To find the charge on one piece of puffed rice, take the square root of this number.

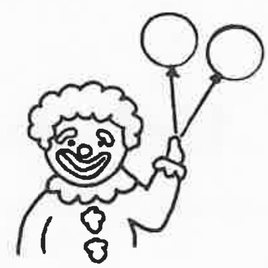
$$q = \sqrt{4 \times 10^{-36}\ \text{C}^2} = \mathbf{2 \times 10^{-18}\ C}$$

Practice Exercises

Exercise 1: When sugar is poured from the box into the sugar bowl, the rubbing of sugar grains creates a static electric charge that repels the grains, and causes sugar to go flying out in all directions. If each of two sugar grains acquires a charge of 3.0×10^{-11} C at a separation of 8.0×10^{-5} m, with what force will they repel each other?

Answer: ____________________

Exercise 2: Boppo the clown carries two mylar balloons that rub against a circus elephant, causing the balloons to separate. Each balloon acquires 2.0×10^{-7} C of charge. How large is the electric force between them when they are separated by a distance of 0.50 m?



Answer: ____________________

Exercise 3: Inez uses hairspray on her hair each morning before going to school. The spray spreads out before reaching her hair partly because of the electrostatic charge on the hairspray droplets. If two drops of hairspray repel each other with a force of 9.0×10^{-9} N at a distance of 0.070 cm, what is the charge on each of the equally-charged drops of hairspray?

Answer: ____________________

Exercise 4: Bonnie is dusting the house and raises a cloud of dust particles as she wipes across a table. If two 4.0×10^{-14}-C pieces of dust exert an electrostatic force of 2.0×10^{-12} N on each other, how far apart are the dust particles at that time?

Answer: ____________________

Exercise 5: Each of two hot-air balloons acquires a charge of 3.0×10^{-5} C on its surface as it travels through the air. How far apart are the balloons if the electrostatic force between them is 8.1×10^{-2} N?

Answer: ____________________

15-2 Electric Field

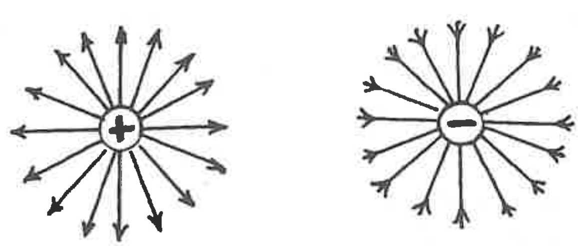
Vocabulary

Electric Field: An area of influence around a charged object. The magnitude of the field is proportional to the amount of electrical force exerted on a positive test charge placed at a given point in the field.

$$\textbf{electric field} = \frac{\textbf{electric force}}{\textbf{test charge}} \quad \text{or} \quad E = \frac{F}{q_0}$$

The SI unit of electric field is the **newton per coulomb (N/C).**

The electric field around a charged object is a vector and can be represented with electric field lines that point in the direction of the force exerted on a unit of positive charge. In other words, electric field lines point away from a positive charge and toward a negative charge, as shown in the diagram.



For a point charge (or other spherical charge distribution), the magnitude of the electric field can be written as

$$E = \frac{F}{q_o} = \frac{kq_oq}{q_od^2} = \frac{kq}{d^2}$$

where q is the charge on the surface of the object, and d is the distance between the center of the charged object and a small positive test charge, q_o, placed in the field.

Solved Examples

Example 3: Deepika pulls her wool sweater over her head, which charges her body as the sweater rubs against her cotton shirt. What is the electric field at a location where a 1.60×10^{-19} C-piece of lint experiences a force of 3.2×10^{-9} N as it floats near Deepika? b) What will happen if Deepika now touches a conductor such as a door knob?

a. *Given:* $q_o = 1.60 \times 10^{-19}$ C
$F = 3.2 \times 10^{-9}$ N

Unknown: $E = ?$
Original equation: $F = q_oE$

Solved: $E = \frac{F}{q_o} = \frac{3.2 \times 10^{-9}\ \text{N}}{1.60 \times 10^{-19}\ \text{C}} = \mathbf{2.0 \times 10^{10}\ N/C}$

b. She will reduce her charge in a process called **grounding,** in which excess electrons flow from her body into the ground and spread evenly over the surface of Earth.

Example 4: A fly accumulates 3.0×10^{-10} C of positive charge as it flies through the air. What is the magnitude and direction of the electric field at a location 2.0 cm away from the fly?

Solution: First, convert cm to m. 2.0 cm = 0.020 m

Given: $k = 9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$
$q = 3.0 \times 10^{-10}$ C
$d = 0.020$ m

Unknown: $E = ?$
Original equation: $E = \frac{kq}{d^2}$

Solve: $E = \frac{kq}{d^2} = \frac{(9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2)(3.0 \times 10^{-10}\ \text{C})}{(0.020\ \text{m})^2} =$ **6800 N/C away from the fly**

Practice Exercises

Exercise 6: Mr. Patel is photocopying lab sheets for his first period class. A particle of toner carrying a charge of 4.0×10^{-9} C in the copying machine experiences an electric field of 1.2×10^{6} N/C as it's pulled toward the paper. What is the electric force acting on the toner particle?

Answer: ____________________

Exercise 7: As Courtney switches on the TV set to watch her favorite cartoon, the electron beam in the TV tube is steered across the screen by the field between two charged plates. If the electron experiences a force of 3.0×10^{-6} N, how large is the field between the deflection plates?

Answer: ____________________

Exercise 8: Gordon the night custodian dusts off a classroom globe with a feather duster, causing the globe to acquire a charge of -8.0×10^{-9} C. What is the magnitude and direction of the electric field at a point 0.40 m from the center of the charged globe?

Answer: ____________________

Exercise 9: April is decorating a tree in her backyard with plastic eggs in preparation for Easter. She hangs two eggs side by side so that their centers are 0.40 m apart. April rubs the eggs to shine them up, and in doing so places a charge on each egg. The egg on the left acquires a charge of 6.0×10^{-6} C while the egg on the right is charged with 4.0×10^{-6} C. What is the electric field at a point 0.15 m to the right of the egg on the left?

Answer: ____________________

15-3 Electrical Potential Difference

Vocabulary

Potential Difference: The work done to move a positive test charge from one location to another.

$$\textbf{potential difference} = \frac{\textbf{work}}{\textbf{test charge}} \quad \text{or} \quad V = \frac{W}{q_0}$$

The SI unit for potential difference is the **volt (V),** which equals a **joule per coulomb (J/C).**

Remember, the term "work" can be replaced with the term "energy," because to store energy in, or give energy to, an object, work must be done. Therefore, potential difference can also be defined as the electrical potential energy per unit test charge. **Voltage** is often used to mean potential difference.

The field that exists between two charged parallel plates is uniform except near the plate edges, and depends upon the potential difference between the plates and the plate separation.

$$\textbf{electric field} = \frac{\textbf{potential difference}}{\textbf{separation between plates}} \quad \text{or} \quad E = \frac{V}{\Delta d}$$

Here, the unit for electric field is the volt/meter. It was noted earlier that the unit for electric field is the newton/coulomb. This means that a volt/meter must equal a newton/coulomb.

$$\frac{\text{volt}}{\text{meter}} = \frac{\text{joule/coulomb}}{\text{meter}} = \frac{\text{newton}\cdot\text{meter}}{\text{coulomb}\cdot\text{meter}} = \frac{\text{newton}}{\text{coulomb}}$$

Solved Examples

Example 5: An electron in Tammie's TV is accelerated toward the screen across a potential difference of 22 000 V. How much kinetic energy does the electron lose when it strikes the TV screen?

Given: $q_o = 1.60 \times 10^{-19}$ C
$V = 22\,000$ V

Unknown: $W = ?$
Original equation: $V = \frac{W}{q_o}$

Solve: $W = q_oV = (1.60 \times 10^{-19}\text{ C})(22\,000\text{ V}) = \mathbf{3.5 \times 10^{-15}\ J}$

Example 6: Amir shuffles his feet across the living room rug, building up a charge on his body. A spark will jump when there is a potential difference of 9000 V between the door and the palm of Amir's hand. This happens when his hand is 0.3 cm from the door. At this point, what is the electric field between Amir's hand and the door?

Solution: First, convert cm to m. 0.3 cm = 0.003 m

Given: $V = 9000$ V
$\Delta d = 0.003$ m

Unknown: $E = ?$
Original equation: $V = E\Delta d$

Solve: $E = \frac{V}{\Delta d} = \frac{9000\text{ V}}{0.003\text{ m}} = \mathbf{3 \times 10^{6}\ V/m}$

Practice Exercises

Exercise 10: James recharges his dead 12.0-V car battery by sending 28 000 C of charge through the terminals. How much electrical potential energy must James store in the car battery to make it fully charged?

Answer: ____________________

Exercise 11: If an electron loses 1.4×10^{-15} J of energy in traveling from the cathode to the screen of Jeffrey's personal computer, across what potential difference must it travel?

Answer: ____________________

Exercise 12: A "bug zapper" kills bugs that inadvertently stray between the charged plates of the device. The bug causes sudden dielectric breakdown of the air between the plates. If two plates in a bug zapper are separated by 5.0 cm and the field between them is a uniform 2.8×10^6 V/m, what is the potential difference that kills the unsuspecting bugs?

Answer: ____________________

Exercise 13: While getting out of a car, Victor builds up a charge on his body as he slides across the cloth car seats. When he attempts to shut the car door, his hand discharges 12 000 V through a uniform electric field of 3.0×10^6 V/m. How far is his hand from the door at the time the spark jumps?

Answer: ____________________

Exercise 14: A lightning bolt from a cloud hits a tree after traveling 200 m to the ground through an electric field of 2.0×10^6 V/m. a) What is the potential difference between the cloud and the tree just before the lightning bolt strikes? b) If you are in an open field during a lightning storm and the only thing you see nearby is a tall tree, is it a good idea to stand under the tree for protection from the lightning? Why or why not?

Answer: **a.** ____________________

Answer: **b.** ____________________

Additional Exercises

A-1: A raindrop acquires a negative charge of 3.0×10^{-18} C as it falls. What is the force of attraction when the raindrop is 6.0 cm from the bulb on the end of a car antenna that holds a charge of 2.0×10^{-6} C?

A-2: In a grain elevator on Farmer Judd's farm, pieces of grain become electrically charged while falling through the elevator. If one piece of grain is charged with 5.0×10^{-16} C while another holds 2.0×10^{-16} C of charge, what is the electrostatic force between them when they are separated by 0.050 m?

A-3: Rocco, an auto body painter, applies paint to automobiles by electrically charging the car's outer surface and oppositely charging the paint particles that he sprays onto the car. This causes the paint to adhere tightly to the car's surface. If two paint particles of equal charge experience a force of 4.0×10^{-8} N between them at a separation of 0.020 cm, what is the charge on each?

A-4: After unpacking a shipment of laboratory glasswear, Mrs. Payne dumps the box of Styrofoam packing chips into a recycling bin. The chips rub together and two chips 0.015 m apart repel each other with a force of 6.0×10^{-3} N. What is the charge on each of the chips?

A-5: Wiz the cat is batting at two Ping-Pong balls hanging from insulating threads with their sides just barely touching. Each ball acquires a positive charge of 3.5×10^{-9} C from Wiz's fur and they swing apart. a) If a force of 6.0×10^{-5} N acts on one of the balls, how far apart are they from each other? b) Is the force between them one of attraction or repulsion?

A-6: A droplet of ink in an ink-jet printer carrying a charge of 8.0×10^{-13} C is deflected onto the paper by a force of 3.2×10^{-4} N. How strong is the field that causes this force?

A-7: In the human body, nerve cells work by pumping sodium ions out of a cell in order to maintain a potential difference across the cell wall. If a sodium ion carries a charge of 1.60×10^{-19} C as it is pumped with an electrical force of 2.0×10^{-12} N, what is the electric field between the inside and outside of the nerve cell?

A-8: Each of two Van de Graaff generators, whose centers are separated from one another by 0.50 m, becomes charged after they are switched on. One Van de Graaff generator holds $+3.0 \times 10^{-2}$ C while the other holds -2.0×10^{-2} C. What is the magnitude and direction of the electric field halfway between them?

A-9: Willa the witch dusts her crystal ball with her silk scarf, causing the ball to become charged with 5.0×10^{-9} C. Willa then stares into the crystal ball and the wart on the end of her nose experiences an electric field strength of 2200 N/C. How far is the tip of her nose from the center of the crystal ball?

A-10: The Millikan oil drop experiment of 1909 allowed Robert A. Millikan to determine the charge of an electron. In the experiment, an oil drop is suspended between two charged plates by an electric force that equals the gravitational force acting on the 1.1×10^{-14}-kg drop. a) What is the charge on the drop if it remains stationary in an electric field of 1.72×10^5 N/C? b) How many extra electrons are there on this particular oil drop?

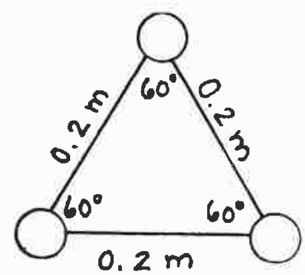
A-11: In eighteenth-century Europe, it was common practice to ring the church bells in an attempt to ward off lightning. However, during one 33-year period, nearly 400 church steeples were struck while the bells were being rung. If a bolt of lightning discharges 30.0 C of charge from a cloud to a steeple across a potential difference of 15 000 V, how much energy is lost by the cloud and gained by the steeple?

A-12: In Exercise A-7, how thick is the wall of the nerve cell if there is a potential difference of 0.089 between the inside and outside of the cell?

A-13: Ulrich stands next to the Van de Graaff generator and gets a shock as he holds his knuckle 0.2 m from the machine. In order for a spark to jump, the electric field strength must be 3×10^6 V/m. At this distance, what is the potential difference between Ulrich and the generator?

Challenge Exercises for Further Study

B-1: Three glass Christmas balls become electrically charged when Noel removes them from the packaging material in their box. Noel hangs the balls on the tree as shown. If each ornament has acquired a charge of 2.0×10^{-10} C, what is the magnitude and direction of the force experienced by the ball at the top?



B-2: In a TV picture tube, electrons are accelerated from rest up to very high speeds through a potential difference of 22 000 V. At what speed will an electron be moving just as it strikes the TV screen? (In reality you would have to consider the effects of relativity in order to solve this exercise properly; however, ignore such relativistic effects here.)

B-3: A lightning bolt discharges into New Hampshire's Lake Winnipesaukee after passing through a potential difference of 9.00×10^7 V. What is the minimum amount of charge the lightning bolt could be carrying, if it were to vaporize 1000. kg of water in the lake that was originally at a temperature of 20.0 °C?

16 Direct Current Circuits

16-1 Current and Resistance

Vocabulary **Current:** The amount of charge that passes through an area in a given amount of time.

$$\textbf{current} = \frac{\textbf{charge}}{\textbf{time}} \quad \text{or} \quad I = \frac{\Delta q}{\Delta t}$$

The SI unit for current is the **ampere (A),** which equals one **coulomb per second (C/s).**

In conductors, such as metal wires, electrons are relatively free to move, and can carry energy throughout a circuit. This energy comes from a source such as a **battery** that converts chemical energy into electrical energy for use in the circuit. As energy is transformed in a battery, a potential difference, V, develops across the battery's terminals. This potential difference is called an **electromotive force,** or **EMF**. In this book, voltage between the terminals of a battery is simply referred to as potential difference.

Vocabulary **Resistance:** An opposition to the flow of charge.

For a given source voltage, the resistance of a circuit determines how much charge will flow in the circuit. When charge passes through a resistance, some electrical energy is changed to other forms. This is produced by a potential difference across the resistance.

$$\textbf{potential difference} = \textbf{(current)(resistance)} \quad \text{or} \quad V = IR$$

The SI unit for resistance is the **ohm (Ω),** which equals one **volt per amp (V/A).**

Sometimes it is not desirable to use wires that have a high resistance, because considerable energy losses occur when charge flows through a resistor. However, in any device that produces heat, such as a toaster, high resistance is needed or else the toaster would not get hot. Therefore, a heating element made with superconducting wires would be useless.

The resistance of a wire depends upon the type of material that the wire is made of, its length, and its cross-sectional area. The longer the wire, the more resistant it is to the flow of charge. The larger the cross-sectional area of the wire, the less resistant it is to charge flow. Temperature also affects the resistance of a wire. The hotter the wire, the more resistant it becomes to the flow of charge. This means that more current will flow through a toaster when it is first turned on than when the coils are glowing red hot.

Solved Examples

Example 1: Household current in a circuit cannot generally exceed 15 A for safety reasons. What is the maximum amount of charge that could flow through this circuit in a house during the course of a 24.0-h day?

Solution: Because the unit ampere means coulombs per second, 24.0 h must be converted in 86 400 s.

Given: $I = 15\text{ A}$
$\Delta t = 86\,400\text{ s}$

Unknown: $\Delta q = ?$
Original equation: $I = \dfrac{\Delta q}{\Delta t}$

Solve: $\Delta q = I\Delta t = (15\text{ A})(86\,400\text{ s}) = \mathbf{1.3 \times 10^6\ C}$

Example 2: What is the resistance of the heating element in a car lock de-icer that contains a 1.5-V battery supplying a current of 0.5 A to the circuit?

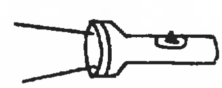
Given: $V = 1.5\text{ V}$
$I = 0.5\text{ A}$

Unknown: $R = ?$
Original equation: $V = IR$

Solve: $R = \dfrac{V}{I} = \dfrac{1.5\text{ V}}{0.5\text{ A}} = \mathbf{3\ \Omega}$

Practice Exercises

Exercise 1: Arthur is going trick-or-treating for Halloween so he puts new batteries in his flashlight before leaving the house. Until the batteries die, it draws 0.500 A of current, allowing a total of 5400. C of charge to flow through the circuit. How long will Arthur be able to use the flashlight before the batteries' energy is depleted?



Answer: ____________________

Exercise 2: Fabian's car radio will run from the 12-V car battery that produces a current of 0.20 A even when the car is turned off. The car battery will no longer operate when it has lost 1.2×10^6 J of energy. If Fabian gets out of the car and leaves the radio on by mistake, how long will it take for the car battery to go completely dead (that is, lose all energy)?

Answer: ____________________

Exercise 3: While cooking dinner, Dinah's oven uses a 220.-V line and draws 8.00 A of current when heated to its maximum temperature. What is the resistance of the oven when it is fully heated?

Answer: ____________________

Exercise 4: Justine's hair dryer has a resistance of 9.00 Ω when first turned on. a) How much current does the hair dryer draw from the 110.-V line in Justine's house? b) What happens to the resistance of the hair dryer as it runs for a long time?

Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 5: Camille takes her pocket calculator out of her bookbag as she gets ready to do her physics homework. In the calculator, a 0.160-C charge encounters 19.0 Ω of resistance every 2.00 seconds. What is the potential difference of the battery?

Answer: ____________________

16-2 Capacitance

Vocabulary **Capacitor:** A device that stores charge on conductors that are separated by an insulator.

Capacitance is a measure of the amount of charge stored on the conductors, for a given potential difference.

$$\textbf{capacitance} = \frac{\textbf{amount of charge}}{\textbf{potential difference}} \quad \text{or} \quad C = \frac{\Delta q}{V}$$

The SI unit for capacitance is the **farad (F),** which equals one **coulomb per volt (C/V).**

A capacitor may be used in a circuit by storing charge on two parallel plates and then periodically releasing it into the circuit, creating an intermittent flow of charge.

Solved Examples

Example 3: The first capacitor was invented by Pieter van Musschenbroek in 1745 when he and his assistant stored charge in a device called a Leyden jar. If 5×10^{-4} C of charge were stored in the jar over a potential difference of 10 000 V, what was the capacitance of the Leyden jar? (When van Musschenbroek touched the jar, he received such a large jolt that he exclaimed he would not try the experiment again for all the kingdom of France!)

Given: $\Delta q = 5 \times 10^{-4}$ C
$V = 10\,000$ V

Unknown: $C = ?$
Original equation: $C = \frac{\Delta q}{V}$

Solve: $C = \frac{\Delta q}{V} = \frac{5 \times 10^{-4}\text{ C}}{10\,000\text{ V}} = \mathbf{5 \times 10^{-8}\ F}$

Example 4: Lydia pushes the shutter button of her camera and the flash unit releases the 4.5×10^{-3} C of charge that was stored in a 500.-μF capacitor. What is the potential difference across the plates of the capacitor inside the flash?

Solution: The term μ (micro) means 10^{-6}, so a μF means 10^{-6} farad.

Given: $\Delta q = 4.5 \times 10^{-3}$ C
$C = 500. \times 10^{-6}$ F

Unknown: $V = ?$
Original equation: $C = \frac{\Delta q}{V}$

Solve: $V = \frac{\Delta q}{C} = \frac{4.5 \times 10^{-3}\text{ C}}{500. \times 10^{-6}\text{ F}} = \mathbf{9.0\ V}$

Practice Exercises

Exercise 6: The nervous system of the human body contains axons whose membranes act as small capacitors. A membrane is capable of storing 1.2×10^{-9} C of charge across a potential difference of 0.070 V before discharging nerve impulses through the body. What is the capacitance of one of these axon membranes?

Answer: ______________________

Exercise 7: During a lightning storm, the separation between the clouds and the earth acts as a giant capacitor with a capacitance of 2500 μF. If the transmitting tower of radio station KBOZ is hit by a bolt of lightning carrying 50. C of charge, what is the potential difference between the cloud and the tower?

Answer: ______________________

Exercise 8: Dr. Frankenstein brings his monster to life with electroshock treatment by discharging a 50.-μF capacitor through the monster's neck across a potential difference of 24 V. How much charge flows into the monster to make him come alive?

Answer: ______________________

Exercise 9: On Saturday nights, Greg likes to go the Frisco Disco, where he can dance under the strobe light. The strobe contains a 200-μF capacitor that stores charge over a 1000-V potential difference. If the strobe flashes 4 times each second, what is the current flow created by the strobe's capacitor?

Answer: ______________________

16-3 Power

Vocabulary **Power:** The amount of work done in a given unit of time.

As seen in the previous chapter, electrical work is done when an amount of charge, Δq, is transferred across a potential difference, V, or $W = \Delta qV$. The faster this transfer of charge occurs, the more power is generated in the circuit.

$$\textbf{Power} = \frac{\textbf{work}}{\textbf{elapsed time}} \quad \text{or} \quad P = \frac{W}{\Delta t} = \frac{\Delta qV}{\Delta t} = IV$$

Therefore, as current is drawn in a circuit to power an appliance, a potential difference occurs across the appliance.

The SI unit for electrical power is the **watt (W),** which equals one **joule per second (J/s).**

Solved Examples

Example 5: The lighter in Bryce's car has a resistance of 4.0 Ω. a) How much current does the lighter draw when it is run off the car's 12-V battery? b) How much power does the lighter use?

a. *Given:* $R = 4.0\ \Omega$, $V = 12\ \text{V}$

Unknown: $I = ?$
Original equation: $V = IR$

Solve: $I = \frac{V}{R} = \frac{12\ V}{4.0\ \Omega} = \mathbf{3.0\ A}$

b. *Given:* $I = 3.0\ \text{A}$, $V = 12\ \text{V}$

Unknown: $P = ?$
Original equation: $P = IV$

Solve: $P = IV = (3.0\ \text{A})(12\ \text{V}) = \mathbf{36\ W}$

Example 6: A 120.-V outlet in Carol's college dorm room is wired with a circuit breaker on a 5-A line so that students cannot overload the circuit. a) If Carol tries to iron a blouse for class with her 700-W iron, will she trip the circuit breaker? b) What is the resistance of the iron?

Solution: A circuit breaker is a switch that automatically turns a circuit off if the current is too high.

a. *Given:* $P = 700.\ \text{W}$, $V = 120.\ \text{V}$

Unknown: $I = ?$
Original equation: $P = IV$

Solve: $I = \frac{P}{V} = \frac{700.\ \text{W}}{120.\ \text{V}} = \mathbf{5.83\ A}$ Yes, she will!

It may be difficult to see how a watt/volt equals an amp until you begin to break down the units.

$$\frac{\text{watt}}{\text{volt}} = \frac{\text{joule/second}}{\text{joule/coulomb}} = \frac{\text{coulomb}}{\text{second}} = \text{amp}$$

b. Now find the resistance using $V = IR$.

Given: $V = 120.\ \text{V}$
$I = 5.83\ \text{A}$

Unknown: $R = ?$
Original equation: $V = IR$

Solve: $R = \frac{V}{I} = \frac{120.\ \text{V}}{5.83\ \text{A}} = \mathbf{20.5\ \Omega}$

Example 7: The Garcias like to keep their 40.0-W front porch light on at night to welcome visitors. If the light is on from 6 p.m. until 7 a.m., and the Garcias pay 8.00¢ per kWh, how much does it cost to run the light for this amount of time each week?

Solution: First, convert the power units to kilowatts, kW, because the cost of household energy is measured in kWh. 40.0 W = 0.0400 kW

Next, determine how long the light is left on each week. From 6 P.M. until 7 A.M. is 13 h. Operating 7 days a week means that the light is on for a total of 91.0 hours.

Given: $P = 0.0400\ \text{kW}$
$\Delta t = 91.0\ \text{h}$

Unknown: $W = ?$ Cost = ?
Original equation: $P = \frac{W}{\Delta t}$

Solve: $W = P\Delta t = (0.0400\ \text{kW})(91.0\ \text{h}) = \mathbf{3.64\ kWh}$

$$\text{Cost} = \frac{8.00¢}{1.00\ \text{kWh}}(3.64\ \text{kWh}) = \mathbf{29.1¢}$$

Therefore, it costs the Garcias about 29¢ to run the light all night for an entire week, or a little over $15 per year.

Practice Exercises

Exercise 10: How much power is used by a contact lens heating unit that draws 0.070 A of current from a 120-V line?

Answer: ____________________

Exercise 11: Celeste's air conditioner uses 2160 W of power as a current of 9.0 A passes through it. a) What is the voltage drop when the air conditioner is running? b) How does this compare to the usual household voltage? c) What would happen if Celeste tried connecting her air conditioner to a usual 120-V line?

Answer: **a.** ____________________

Answer: **b.** ____________________

Answer: **c.** ____________________

Exercise 12: Which has more resistance when plugged into a 120.-V line, a 1400.-W microwave oven or a 150.-W electric can opener?

Answer: ____________________

Exercise 13: Valerie's 180-W electric rollers are plugged into a 120-V line in her bedroom. a) What current do the electric rollers draw? b) What is the resistance of the rollers when they are heated? c) Combining the equations just used, derive an equation that relates power to voltage and resistance.

Answer: **a.** ____________________

Answer: **b.** ____________________

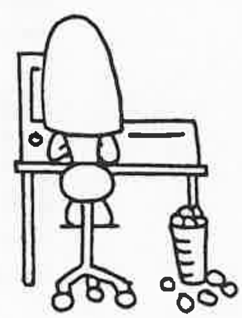
Answer: **c.** ____________________

Exercise 14: Mrs. Olsen leaves her 0.900-kW electric coffee maker on each day as she heads off to work at 6 A.M. because she likes to come home to a hot cup of coffee at 6 P.M. a) If the electric company charges Mrs. Olsen $0.100 per kWh, how much does running the coffee maker cost her each day? b) What is the yearly cost to run the coffee maker?

Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 15: While writing this book, the author spent about 1000 h working on her personal computer that has a power input of 60.0 W. Seventy additional hours were spent with the 60.0-W computer and the 240.-W printer running. How much did it cost for the energy use of these two devices, at a cost of $0.100 per kWh?



Answer: ____________________

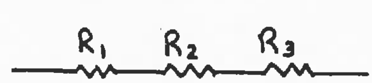
16.4 Series and Parallel Circuits

When multiple resistors are used in a circuit, the total resistance in the circuit must be found before finding the current. Resistors can be combined in a circuit in series or in parallel.

Resistors in Series

When connected in series, the total resistance, R_T, is equal to

$$R_T = R_1 + R_2 + R_3 + \ldots$$



In series, the total resistance is always *larger* than any individual resistance.

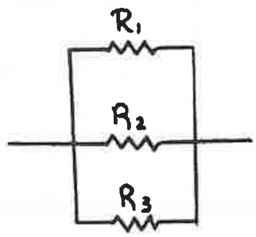
Current in series resistors: In series circuits, charge has only one path through which to flow. Therefore, the current passing through each resistor in series is the same.

Potential difference across series resistors: As charge passes through each of the resistors, it loses some energy. This means that there will be a potential difference across each resistor. The sum of all the potential differences equals the potential difference across the battery, assuming negligible resistance in the connecting wires.

Resistors in Parallel

When connected in parallel, the total resistance, R_T, is equal to

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$



Don't forget! After finding a common denominator and determining the sum of these fractions, flip over the answer to determine R_T.

In parallel circuits, the total resistance is always *smaller* than any individual resistance.

Current in parallel resistors: In parallel circuits, there is more than one possible path and current divides itself according to the resistance of each path. Since current will take the "path of least resistance," the smallest resistor will allow the most current through, while the largest resistor will allow the least current through. The sum of the currents in each parallel resistor equals the original current entering the branches.

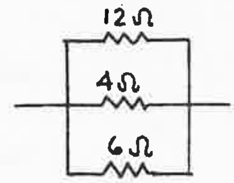
Potential difference in parallel resistors: The potential difference across each of the resistors in a parallel combination is the same. If there are no other resistors in the circuit, it is equal to the potential difference across the battery, assuming negligible resistance in the connecting wires.

Solved Examples

Example 8: Find the total resistance of the three resistors connected in series.

Solve: $R_T = R_1 + R_2 + R_3 = 12\ \Omega + 4\ \Omega + 6\ \Omega = \mathbf{22\ \Omega}$

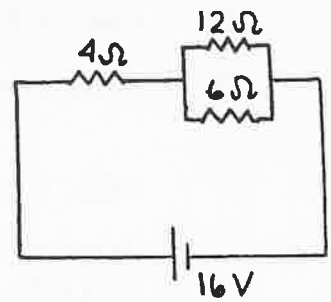
Example 9: Find the total resistance of the same three resistors now connected in parallel.



Solve: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{12\ \Omega} + \frac{1}{4\ \Omega} + \frac{1}{6\ \Omega}$

$\frac{1}{R_T} = \frac{1}{12\ \Omega} + \frac{3}{12\ \Omega} + \frac{2}{12\ \Omega} = \frac{6}{12\ \Omega} = \frac{1}{2\ \Omega}$ $R_T = \mathbf{2\ \Omega}$

Example 10: Find the total current passing through the circuit.



This circuit contains resistors in parallel that are then combined with a resistor in series. Always begin solving such a resistor combination by working from the inside out. In other words, first determine the equivalent resistance of the two resistors in parallel before combining this total resistance with the one in series.

Look first at the parallel combination.

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{12\ \Omega} + \frac{1}{6\ \Omega} = \frac{1}{12\ \Omega} + \frac{2}{12\ \Omega} = \frac{3}{12\ \Omega} = \frac{1}{4\ \Omega}$$

$R_T = \mathbf{4\ \Omega}$

Now, combine this equivalent resistance with the resistor in series.

$$R_T = R_1 + R_2 = 4\ \Omega + 4\ \Omega = \mathbf{8\ \Omega}$$

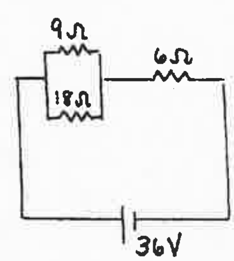
To find the current flowing through the circuit, use this total resistance in combination with the potential difference from the battery.

Given: $V = 16\ \text{V}$
$R = 8\ \Omega$

Unknown: $I = ?$
Original equation: $V = IR$

Solve: $I = \frac{V}{R} = \frac{16\ \text{V}}{8\ \Omega} = \mathbf{2\ A}$

Example 11: Find the current in the 9-Ω resistor.



For the parallel branch

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{9\ \Omega} + \frac{1}{18\ \Omega} = \frac{2}{18\ \Omega} + \frac{1}{18\ \Omega} = \frac{3}{18\ \Omega} = \frac{1}{6\ \Omega}$$

$R_T = \mathbf{6\ \Omega}$

Combining with the series resistor

$$R_T = R_1 + R_2 = 6\ \Omega + 6\ \Omega = \mathbf{12\ \Omega}$$

Given: $V = 36\ \text{V}$
$R = 12\ \Omega$

Unknown: $I = ?$
Original equation: $V = IR$

Solve: $I = \frac{V}{R} = \frac{36\ \text{V}}{12\ \Omega} = \mathbf{3\ A}$

This 3 A is the current through the entire circuit. Use this current to find the potential difference across the parallel combination. Remember, the potential difference across resistors wired in parallel is the same regardless of which path is taken. Because the resistors in parallel have a combined resistance of 6 Ω, you find the potential difference across the parallel branch as follows.

Given: $R = 6\ \Omega$
$I = 3\ \text{A}$

Unknown: $V = ?$
Original equation: $V = IR$

Solve: $V = IR = (3\ \text{A})(6\ \Omega) = \mathbf{18\ V}$

Therefore, the potential difference across both the top and the bottom branches is 18 V. Now use this 18-V drop to determine the current in the 9-Ω resistor.

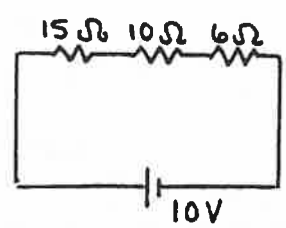
Given: $V = 18\ \text{V}$
$R = 9\ \Omega$

Unknown: $I = ?$
Original equation: $V = IR$

Solve: $I = \frac{V}{R} = \frac{18\ \text{V}}{9\ \Omega} = \mathbf{2\ A}$

Practice Exercises

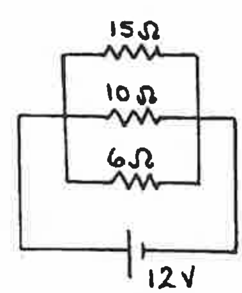
Exercise 16: Using the diagram, a) find the total resistance in the circuit. b) Find the total current through the circuit.



Answer: **a.** ____________________

Answer: **b.** ____________________

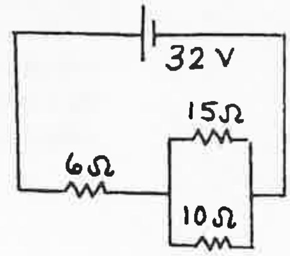
Exercise 17: Using the diagram, a) find the total resistance in the circuit. b) Find the total current through the circuit.



Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 18: Using the diagram, a) find the total resistance in the circuit. b) Find the total current through the circuit.



Answer: **a.** ____________________

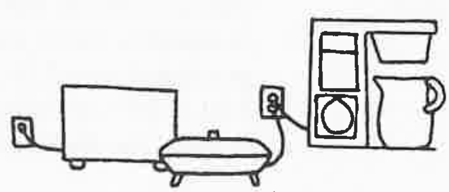
Answer: **b.** ____________________

Exercise 19: Old-fashioned holiday lights were connected in series across a 120-V household line. a) If a string of these lights consists of 12 bulbs, what is the potential difference across each bulb? b) If the bulbs were connected in parallel, what would be the potential difference across each bulb?

Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 20: Before going to work each morning, Gene runs his 18-Ω toaster, 11-Ω electric frying pan, and 14-Ω electric coffee maker, all at the same time. The three are connected in parallel across a 120-V line. a) What is the current through each appliance? b) If a household circuit could carry a maximum current of 15 A, would Gene be able to run all of these appliances at the same time?



Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 21: Timmy is playing with a new electronics kit he has received for his birthday. He takes out four resistors with resistances of 15 Ω, 20 Ω, 20 Ω, and 30 Ω. a) How would Timmy have to wire the resistors so that they would allow the maximum amount of current to be drawn? Calculate the total resistance in this circuit. b) How must he wire the resistors so that they draw a minimum amount of current? Calculate the total resistance in this circuit.

Answer: **a.** __________________

Answer: **b.** __________________

Exercise 22: Farmer Crockett is preparing tomato seedlings for his spring planting by growing the small plants over five 46-Ω strip heaters wired in parallel. a) How much current does each heater draw from a 120-V line? b) How much current do they draw all together?

Answer: **a.** __________________

Answer: **b.** __________________

Additional Exercises

A-1: Otto accidently leaves his automobile headlights on overnight and is unable to start his car in the morning. Each of the two headlights connected in parallel draws 2.00 A of current from the 12.0-V battery. If the battery stores 7.50×10^5 J of energy, how long will it take for the headlights to go off? b) Why are the headlights connected in parallel?

A-2: Officer Moynihan is patrolling his beat with a 4.5-V flashlight whose lightbulb has a resistance of 12 Ω. How much current does the flashlight draw?

A-3: Each night before falling asleep, Linus turns on his electric blanket that is plugged into the 120.-V electrical outlet. A current of 1.20 A flows through the blanket. a) What is the blanket's resistance? b) Does Linus want his electric blanket to have a high resistance or a low resistance? Why?

A-4: Herbert had just suffered a heart attack but he was revived in the hospital emergency room with a device called a defibrillator. (The paddles of a defibrillator supply a short pulse of high voltage to restart the heart.) The defibrillator contains a 20.-μF capacitor that releases 0.15 C of charge. a) What is the potential difference between the defribrillator paddles during the discharge? b) Why do you think doctors yell "Clear!" to the attendants before discharging the defibrillator?

A-5: Sherm is typing his term paper on a computer that contains a high-speed switch, controlled with a small 100×10^{-12} F speed-up capacitor. What is the current flow created by the capacitor if it discharges every 0.1 s across a potential difference of 5 V?

A-6: Every Sunday morning Stuart makes "breakfast in bed" for his wife. However, because the household wires can only carry a maximum current of 15 A from the 120.-V line, it is difficult to run all of the appliances simultaneously without blowing a fuse. What is the most power Stuart may use while cooking, before blowing a fuse?

A-7: In the previous exercise, a) how much current will Stuart draw if he tries to run the 700.-W toaster and 1000.-W coffee maker at the same time? b) Will this cause him to blow the fuse?

A-8: Xiaoyi's aquarium operates for 24.0 h a day and contains a 5.0-W heater, two 20.0-W lightbulbs, and a 35.0-W electric filter. If Xiaoyi pays $0.100 per kWh for her electricity bill, how much will it cost to maintain the aquarium for 30.0 days?

A-9: The average power plant, running at full capacity, puts out 500. MW of power. If the power company charges its customers $0.10 per kWh, what is the revenue brought in by the power plant each day?

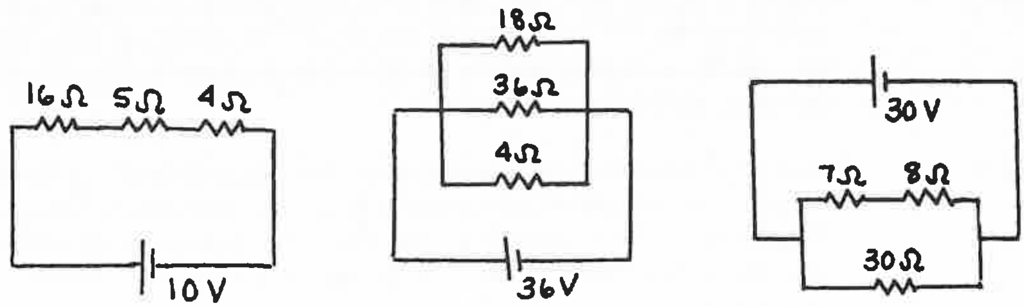
A-10: Horace has invented a unique pair of reading glasses that have two small light bulbs at the bottom wired in series, so that he can see the newspaper when he is reading at night. Each of the bulbs has a resistance of 2.00 Ω, and the system runs off a 3.20-V battery. How much current is drawn by Horace's reading glasses?

A-11: Jay has two 8-Ω stereo speakers wired in series in the front of his car connected to the 4.0-V output of the stereo. a) What is the current through each of the speakers? b) In his garage, Jay finds two more old speakers with resistances of 4 Ω and 16 Ω. He wires each in parallel with the 8-Ω combination. What is the new current through the 8-Ω speakers? c) If the loudness of each speaker is proportional to the amount of power used, how has the loudness of the two 8-Ω speakers changed?

A-12: Find a) the total resistance in circuit A below. b) Find the total current through the circuit.

A-13: Find a) the total resistance in circuit B below. b) Find the total current through the circuit.

A-14: Find a) the total resistance in circuit C below. b) Find the total current through the circuit.

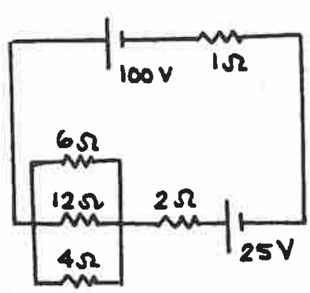


Circuit A   Circuit B   Circuit C

Challenge Exercises for Further Study

B-1: An 800.-W submersible electric heater is put into a 20.0 °C hottub until the 50.0-kg of tub water has warmed up to 70.0 °C. How long will it take for the heater to heat the tub water? (c_{water} = 4187 J/kg°C)

B-2: Find the total current in the circuit in the diagram.



B-3: In exercise A-10, the light bulbs are rated for 5 h of use before they burn out. If the battery can supply 5184 J to the circuit, which occurs first, energy depletion in the battery or failure of a bulb?