COULOMB'S LAW The size or magnitude of the **electrostatic force** between two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. This relationship, called **Coulomb's law,** is given by this equation.

$$F_e = \frac{kq_1q_2}{r^2}$$

F_e is the electrostatic force in newtons, q_1 and q_2 are the charges in coulombs, and r is the distance of separation in meters. The electrostatic constant, k, is equal to $8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$. The electrostatic force is directed along the line joining the charges. The force that q_1 exerts on q_2 is equal in magnitude but opposite in direction to the force that q_2 exerts on q_1. The Coulomb's law equation is valid for charged objects whose dimensions are small compared with the distance separating the objects.

SAMPLE PROBLEM

What is the electrostatic force between two small spheres possessing net charges of +2.0 microcoulombs and −3.0 microcoulombs, respectively, if the distance between them is 10.0 meters?

Solution: Identify the known and unknown values.

Known	*Unknown*
$k = 8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$	$F_e = ?\ \text{N}$
$q_1 = +2.0 \times 10^{-6}\ \text{C}$	
$q_2 = -3.0 \times 10^{-6}\ \text{C}$	
$r = 10.0\ \text{m}$	

Substitute the known values into the Coulomb's law equation and solve.

$$F_e = \frac{kq_1q_2}{r^2}$$

$$F_e = \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(+2.0 \times 10^{-6}\ \text{C})(-3.0 \times 10^{-6}\ \text{C})}{(1.00 \times 10^1\ \text{m})^2}$$

$$F_e = \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(-6.0 \times 10^{-12}\ \text{C}^2)}{1.00 \times 10^2\ \text{m}^2}$$

$$F_e = -5.4 \times 10^{-6}\ \text{N}$$

The negative sign indicates a force of attraction.

Review Questions

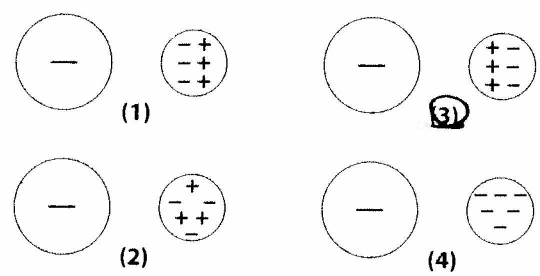
1. What is the charge of a proton? (1) 9.11×10^{-31} C (2) 1.67×10^{-27} C (3) 1.60×10^{-19} C (4) 6.25×10^{18} C

2. A charge of 100 elementary charges is equivalent to (1) 1.60×10^{-21} C (2) 1.60×10^{-17} C (3) 6.25×10^{16} C (4) 6.25×10^{20} C

3. Compare the sign and magnitude of the charge on a proton to the sign and magnitude of the charge on an electron. Both 1.6×10^{-19}, sign different

4. Which particle has no charge? (1) neutron (2) proton (3) electron (4) ion

5. A small, uncharged metal sphere is placed near a large, negatively charged sphere. Which diagram best represents the charge distribution of the smaller sphere?



6. Which net charge could be found on an object? (1) 8.00×10^{-20} C (2) 2.40×10^{-19} C (3) 3.20×10^{-19} C (4) 6.25×10^{-18} C

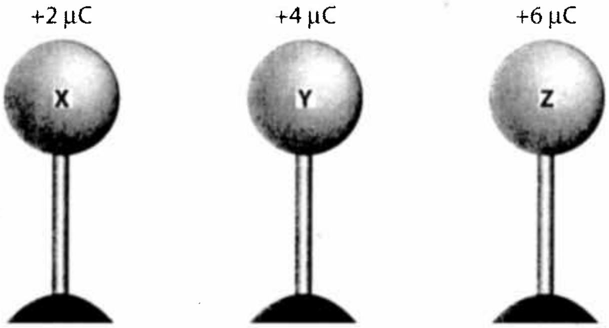
7. One of two identical metal spheres has a charge of $+q$ and the other sphere has a charge of $-q$. The spheres are brought together and then separated. Compared to the total charge on the two spheres before contact, the total charge on the spheres after contact is (1) less (2) greater (3) the same

8. After two neutral solids, A and B, were rubbed together, Solid A acquired a net negative charge. Solid B, therefore, experienced a net (1) loss of electrons (2) increase of electrons (3) loss of protons (4) increase of protons

9. A rod and a piece of cloth are rubbed together. If the rod acquires a charge of $+1 \times 10^{-6}$ coulomb, the cloth acquires a charge of (1) 0 C (2) $+1 \times 10^{-6}$ C (3) -1×10^{-6} C (4) $+1 \times 10^{+6}$ C

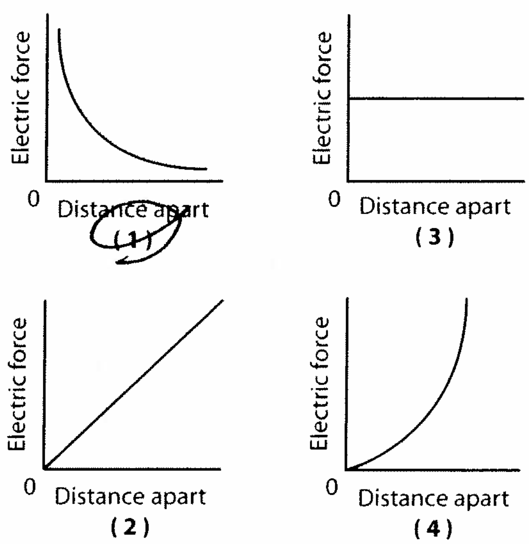
10. Two identical spheres, A and B, carry charges of +6 microcoulombs and −2 microcoulombs, respectively. If these spheres touch, what will be the resulting charge on sphere A? 2 mC

11. The diagram below shows the initial charges and positions of three identical metal spheres, X, Y, and Z, which have been placed on insulating stands.



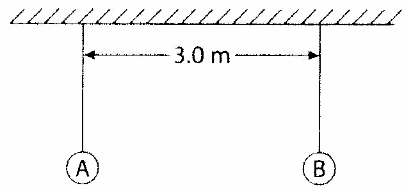
All three spheres are simultaneously brought into contact with each other and then returned to their original positions. Which statement best describes the charge of the spheres after this procedure is completed? (1) All the spheres are neutral. (2) Each sphere has a net charge of +4 μC. (3) Each sphere retains the same charge that it had originally. (4) Sphere Y has a greater charge than sphere X or sphere Z.

12. Two oppositely charged metal spheres are brought toward each other. Which graph best represents the relationship between the magnitude of the electric force between the spheres and the distance between them?



13. The electrostatic force of attraction between two small spheres that are 1.0 meter apart is F. If the distance between the spheres is decreased to 0.5 meter, the electrostatic force will be (1) $\frac{F}{2}$ (2) $2F$ (3) $\frac{F}{4}$ (4) $4F$

14. The diagram below shows two metal spheres suspended by strings and separated by a distance of 3.0 meters. The charge on sphere A is $+5.0 \times 10^{-4}$ coulomb, and the charge on sphere B is $+3.0 \times 10^{-5}$ coulomb.



Which statement best describes the electrical force between the spheres? (1) It has a magnitude of 15 N and is repulsive. (2) It has a magnitude of 45 N and is repulsive. (3) It has a magnitude of 15 N and is attractive. (4) It has a magnitude of 45 N and is attractive.

15. Two identical small spheres possessing charges q_1 and q_2 are separated by distance r. Which change would produce the greatest increase in the electrical force between the two spheres? (1) doubling charge q_1 (2) doubling r (3) doubling r and charge q_1 (4) doubling r and charges q_1 and q_2

16. If the charge on each of two small spheres a fixed distance apart is doubled, the electrostatic force between the spheres will be (1) halved (2) doubled (3) quartered (4) quadrupled

17. A point charge of $+3.0 \times 10^{-7}$ coulomb is placed 2.0×10^{-2} meter from a second point charge of $+4.0 \times 10^{-7}$ coulomb. What is the magnitude of the electrostatic force between the charges?

Electric Fields

An **electric field** is the region around a charged particle through which a force is exerted on another charged particle. An **electric field line** is the imaginary line along which a positive test charge would move in an electric field. The direction of an electric field is the direction of the force on a stationary positive test charge located at any point on a field line. On a curved field line, the direction of the field at any point is the tangent drawn to the field line at that point. Electric field lines begin on positive charges (or at infinity) and end on negative charges (or infinity). Field lines never intersect.

W is the work in joules, *q* is the charge in coulombs, and *V* is the potential difference in joules per coulomb. If one joule of work is done to move one coulomb of charge between two points in an electric field, a potential difference of one **volt** is said to exist between the two points. That is, 1 joule/coulomb = 1 volt. The volt, V, is the derived SI unit for potential difference.

If an elementary charge is moved against an electric field through a potential difference of one volt, the work done on the charge is calculated as shown below.

$$W = Vq = (1.00\ \text{V})(1.60 \times 10^{-19}\ \text{C}) = 1.60 \times 10^{-19}\ \text{J}$$

This amount of work (1.60×10^{-19} J), or gain in potential energy, is called the **electronvolt,** eV. That is, 1.00 eV = 1.60×10^{-19} J.

SAMPLE PROBLEM

Moving a point charge of 3.2×10^{-19} coulomb between points A and B in an electric field requires 4.8×10^{-18} joule of energy. What is the potential difference between these points?

Solution: Identify the known and unknown values.

Known	*Unknown*
$q = 3.2 \times 10^{-19}$ C	$V = ?$ V
$W = 4.8 \times 10^{-18}$ J	

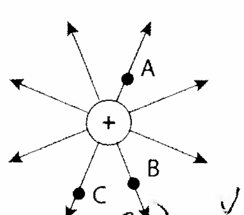
Substitute the known values into the equation for potential difference and solve.

$$V = \frac{W}{q} = \frac{4.8 \times 10^{-18}\ \text{J}}{3.2 \times 10^{-19}\ \text{C}} = 15\ \text{V}$$

Review Questions

18. What is the magnitude of the electrostatic force experienced by one elementary charge at a point in an electric field where the electric field strength is 3.0×10^3 newtons per coulomb? (1) 1.0×10^3 N (2) 1.6×10^{-19} N (3) 3.0×10^3 N (4) 4.8×10^{-16} N

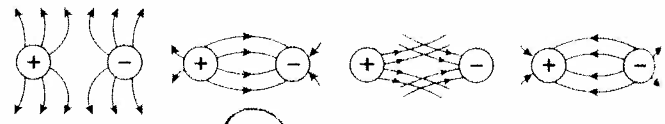
19. The diagram below shows some of the lines of electric force around a positive point charge.



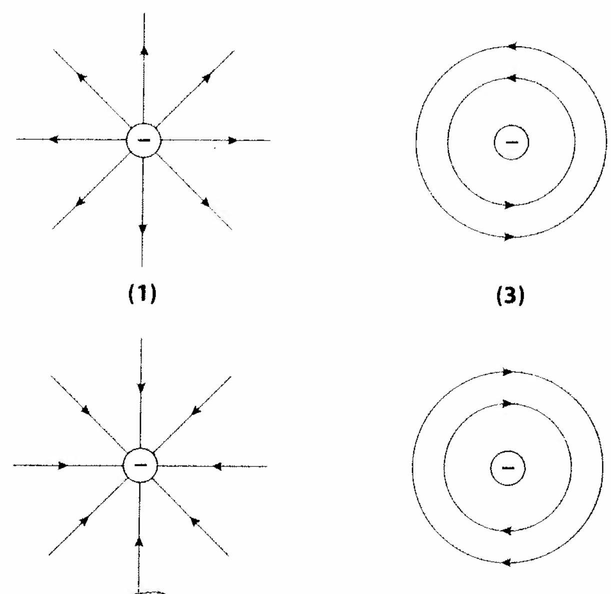
The strength of the electric field is (1) greatest at point A (2) greatest at point B (3) greatest at point C (4) equal at points A, B, and C

20. A charged particle is placed in an electric field *E*. If the charge on the particle is doubled, the magnitude of the force exerted on the particle by the field *E* is (1) unchanged (2) doubled (3) halved (4) quadrupled

21. Which diagram best illustrates the electric field around two unlike charges?



22. Which diagram best represents the electric field of a point negative charge?



23. How much energy is needed to move one electron through a potential difference of 1.0×10^2 volts? (1) 1.0 J (2) 1.0×10^2 J (3) 1.6×10^{-17} J (4) 1.6×10^{-19} J

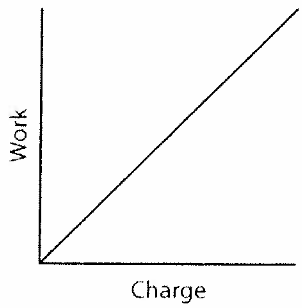
24. 6.0 joules of work are done to move 2.0 coulombs of charge from point A to point B. Determine the potential difference between points A and B.

25. A helium ion with a charge of $+2e$ is accelerated by a potential difference of 5.0×10^3 volts. What is the kinetic energy acquired by the ion? (1) 3.2×10^{-19} eV (2) 2.0 eV (3) 5.0×10^3 eV (4) 1.0×10^4 eV

26. If 4 joules of work are required to move 2 coulombs of charge through a 6-ohm resistor, what is the potential difference across the resistor?

27. An electron is accelerated from rest through a potential difference of 200. volts. What is the work done on the electron in electron volts?

28. The graph below shows the relationship between the work done on a charged body in an electric field and the net charge on the body.



What does the slope of the graph represent?

Electric Current

Electric **current** is the rate at which charge passes a given point in a circuit. An **electric circuit** is a closed path along which charged particles move. A **switch** is a device for making, breaking, or changing the connections in an electric circuit. Figure 4-3 shows the symbol for a switch.

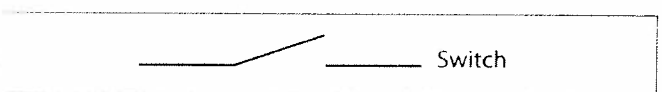


Figure 4-3. The symbol for a switch

UNIT OF CURRENT The SI unit of electric current, I, is the **ampere,** A. It is a fundamental unit. The coulomb, C, the unit of charge, is a derived unit defined to be the amount of charge that passes a point when a current of one ampere flows for one second. This relationship can be expressed as follows:

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

I is current in amperes, q is charge in coulombs, and t is time in seconds. An **ammeter** is a device used to measure current. The symbol for an ammeter is shown in Figure 4-4.

Figure 4-4. The symbol for an ammeter

CONDITIONS NECESSARY FOR AN ELECTRIC CURRENT In addition to a complete circuit, a difference in potential between two points in the circuit must exist for there to be an electric current. The potential difference may be supplied by a **cell,** a device that converts chemical energy to electrical energy, or a **battery,** a combination of two or more electrochemical cells. The potential difference can be measured with a device called a **voltmeter.** These devices are represented in an electric circuit diagram by the symbols shown in Figure 4-5.

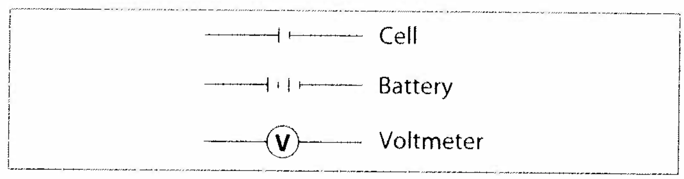


Figure 4-5. Symbols for sources of potential difference (voltage) and a voltmeter for measuring potential difference

Positive charges tend to move from points of higher potential to points of lower potential, or from positive potential to negative potential. Negative charges tend to move in the opposite direction. The direction of a current in an electric circuit can be defined as either of these directions. In some mathematical treatments it is convenient to treat the current as flowing from positive to negative, that is, as conventional current. However, it is more natural to choose the electron flow as the direction of current, because most currents consist of electrons in motion. This is the definition used in this book.

CONDUCTIVITY IN SOLIDS For a current to exist in an electric circuit, the circuit must consist of materials through which charge can move. The ability of a material to conduct electricity depends on the number of free charges per unit volume and on their mobility. **Conductivity** is a property of a material that depends on the availability of charges that are relatively free to move under the influence of an electric field. Pure metals have many electrons, and these electrons are not bound, or are only loosely bound, to any particular atom. Consequently, metals are good **conductors,**

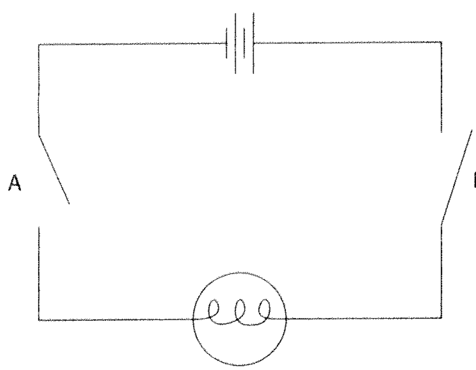
Review Questions

29. 20.0 coulombs of charge pass a given point in a conductor in 4.0 seconds. Determine the current in the conductor.

30. A wire carries a current of 2.0 amperes. How many electrons pass a given point in this wire in 1.0 second? (1) 1.3×10^{18} (2) 2.0×10^{18} (3) 1.3×10^{19} (4) 2.0×10^{19}

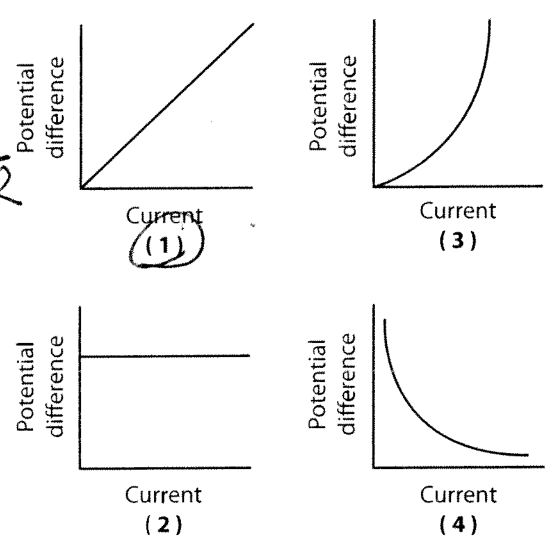
31. Which condition must exist between two points in a conductor in order to maintain a flow of charge? (1) a potential difference (2) a magnetic field (3) a low resistance (4) a high resistance

32. In the diagram below, which of the switches must be closed in order for the lamp to light?

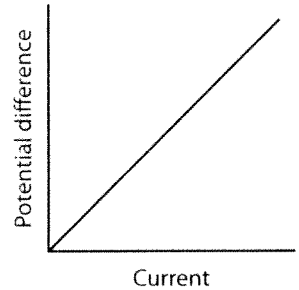


(1) A only (2) B only (3) both A and B

33. Which graph best represents the relationship between potential difference applied to a conductor and the resulting current through the conductor? (Assume constant temperature.)



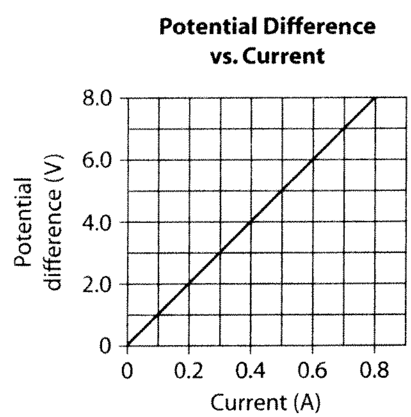
34. The graph below shows the relationship between potential difference and current in a simple circuit.



For any point on the line, what does the ratio of potential difference to current represent? (1) work in joules (2) power in watts (3) resistance in ohms (4) charge in coulombs

35. A 20.-ohm resistor has 40. coulombs of charge passing through it in 5.0 seconds. What is the potential difference across the resistor? (1) 8.0 V (2) 1.0×10^2 V (3) 1.6×10^2 V (4) 2.0×10^2 V

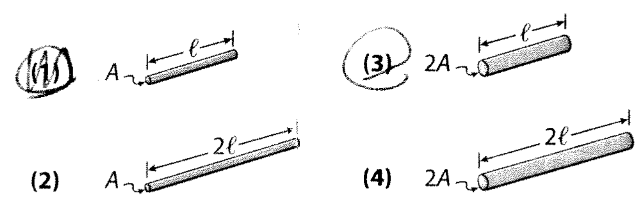
36. The graph below represents the relationship between the potential difference across a metal conductor and the current through the conductor at constant temperature.



What is the resistance of the conductor? (1) 1 Ω (2) 0.01 Ω (3) 0.1 Ω (4) 10 Ω

37. A potential difference of 12 volts is applied across a circuit having a 4.0-ohm resistance. What is the current in the circuit?

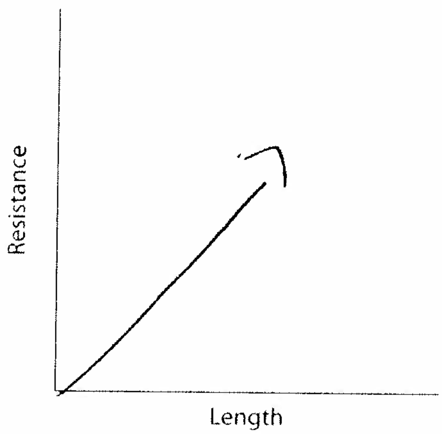
38. In the diagrams below, ℓ represents a unit length of copper wire and A represents a unit cross-sectional area. Which copper wire has the smallest resistance at room temperature?



39. If the temperature of a metal conductor is reduced, its resistance will usually (1) decrease (2) increase (3) remain the same

40. The resistance of a wire at constant temperature depends on the wire's (1) length only (2) type of metal only (3) length and cross-sectional area only (4) length, type of metal, and cross-sectional area

41. On the axes below, sketch the general shape of the graph that shows the relationship between the resistance of a copper wire of uniform cross-sectional area and the wire's length at constant temperature.



42. A piece of wire has a resistance of 8 ohms. What is the resistance of a second piece of wire of the same composition, same diameter, and at the same temperature, but with one half the length of the first wire?

43. An aluminum wire has a resistance of 48 ohms. A second aluminum wire of the same length and at the same temperature, but with twice the cross-sectional area, would have a resistance of (1) 12 Ω (2) 24 Ω (3) 48 Ω (4) 96 Ω

44. What is the resistance of a 10.0-meter long copper wire having a cross-sectional area of 1.50×10^{-6} m^2 at 20°C? (1) 1.15×10^{-1} Ω (2) 1.15×10^{-2} Ω (3) 1.15×10^{-13} Ω (4) 1.15×10^{-14} Ω

45. A 5.00-meter long tin wire has a cross-sectional area of 2.00×10^{-6} m^2 and a resistance of 0.35 ohm. Determine the resistivity of tin.

46. At 20°C carbon has a resistivity of 3.5×10^{-5} Ω · m. What is the ratio of the resistivity of carbon to the resistivity of copper? (1) 1:2 (2) 2:1 (3) 200:1 (4) 2000:1

47. Unlike most metals, the resistivity of carbon decreases with increasing temperature. As the temperature of carbon increases, its resistance (1) decreases (2) increases (3) remains the same

48. An aluminum wire and a tungsten wire have the same cross-sectional area and the same resistance at 20°C. If the aluminum wire is 4.0×10^{-2} meter long, what is the length of the tungsten wire? (1) 1.0×10^{-2} m (2) 2.0×10^{-2} m (3) 4.0×10^{-2} m (4) 8.0×10^{-2} m

Electric Circuits

The simplest electric circuit consists of a source of electrical energy, such as a battery; connecting wires; and a circuit element, such as a lamp or a resistor, that converts electrical energy to light or heat. The current in the circuit is dependent on the potential difference V provided by the battery at the ends of the circuit element, and the resistance R of the circuit element. These quantities are related to each other by Ohm's Law, $I = \frac{V}{R}$. Figure 4-7 shows a simple electric circuit.

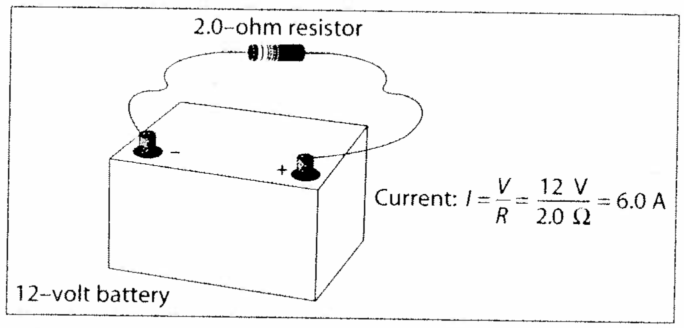


Figure 4-7. A simple circuit

When two or more resistors are present in a circuit, there are two basic methods of connecting them—in series or in parallel.

SERIES CIRCUITS A **series circuit** is a circuit in which all parts are connected end to end to provide a single path for the current. Figure 4-8 shows three resistors connected in series with a battery. The resistors are differentiated by the use of subscripts R_1, R_2, and R_3.

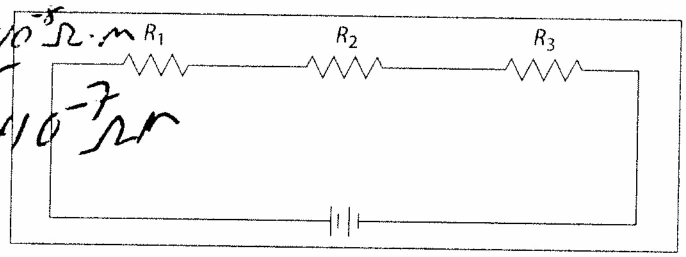


Figure 4-8. Resistors in a series circuit