Since the ball is in equilibrium the first condition of equilibrium is applied as

$$\Sigma F_y = 0, \qquad \Sigma F_x = 0$$

$$T_y - w = 0, \qquad F_e - T_x = 0$$

$$T \sin\theta = w, \qquad F_e = T\cos\theta$$

$$\frac{F_e}{w} = \frac{T\cos\theta}{T\sin\theta} = \frac{1}{\tan\theta}$$

$$F_e = \frac{w}{\tan\theta}$$

$$\frac{kq^2}{r^2} = \frac{mg}{\tan\theta}$$

Solving for the charge q on each ball we get

$$q = \sqrt{\frac{r^2mg}{k\tan\theta}}$$

The angle θ, found from the geometry of the figure 18.18(a), is

$$\theta = \cos^{-1}\frac{r/2}{l}$$

$$= \cos^{-1}\frac{5.00\ \text{cm}}{25.0\ \text{cm}} = 78.5°$$

Therefore, the charge on each ball is

$$q = \sqrt{\frac{r^2mg}{k\tan\theta}}$$

$$= \sqrt{\frac{(0.100\ \text{m})^2(5.00 \times 10^{-3}\ \text{kg})(9.80\ \text{m/s}^2)}{(9.00 \times 10^9\ \text{N m}^2/\text{C}^2)\tan 78.5°}}$$

$$= 1.05 \times 10^{-7}\ \text{C}$$

The tension in the string is

$$T\sin\theta = w$$

$$T = \frac{w}{\sin\theta} = \frac{mg}{\sin\theta}$$

$$= \frac{(5.00 \times 10^{-3}\ \text{kg})(9.80\ \text{m/s}^2)}{\sin 78.5°}$$

$$= 5.00 \times 10^{-2}\ \text{N}$$

The Language of Physics

Electrostatics
The study of electric charges at rest under the action of electric forces (p. 517).

The fundamental principle of electrostatics
Like electric charges repel each other, whereas unlike electric charges attract each other (p. 518).

Quarks
Elementary particles of matter. There are six quarks. They are up, down, strange, charm, bottom, and top. The proton and neutron are made of quarks, but the electron is not (p. 520).

Conductors
Materials that permit the free flow of electric charge through them (p. 521).

Insulators or dielectrics
Materials that do not permit the free flow of electric charge through them (p. 521).

Coulomb's law
The force between point charges q_1 and q_2 is directly proportional to the product of their charges and inversely proportional to the square of the distance separating them. The direction of the force lies along the line separating the charges (p. 523).

Summary of Important Equations

Coulomb's law

$$F = \frac{kq_1q_2}{r^2} \qquad (18.1)$$

Force caused by multiple charges

$$\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + \mathbf{F}_4 + \cdots \qquad (18.3)$$

Questions for Chapter 18

1. Describe the process of charging by induction.

†2. What did Ben Franklin have to do with the classification of electrical charge?

3. The difference between one chemical element and another is the number of protons that each contains. Is it possible for one chemical element to have the same number of neutrons as another chemical element?

4. Discuss the planetary model of the atom and state its good points and its limitations.

†5. Is it possible for a quark to exist if it has not been seen? If it cannot be isolated does it make any sense to describe particles as though they were made up of quarks?

†6. Describe the process of lightning in the atmosphere. How do the earth and the clouds pick up electric charge? If air is an insulator, how can a lightning bolt ever reach the ground?

7. Can you think of a way that you could use electrostatics to measure the humidity of the atmosphere?

8. How could you paint a metallic object with a minimum of paint using the principles of electrostatics?

†9. Describe the phenomenon known as "St. Elmo's Fire" in terms of electrostatics.

10. Why do clothes taken from a clothes dryer sometimes cling to the body?

Problems for Chapter 18

18.4 Coulomb's Law

1. How many electrons are contained in a charge of 3 μC?

2. A point charge of 4.00 μC is placed 25.0 cm from another point charge of -5.00 μC. Calculate the magnitude and direction of the force on each charge.

3. A point charge q_1 of 2.53 μC is placed 1.00 m in front of a second point charge q_2 of 8.64 μC. Find the magnitude and direction of the force on q_1.

4. If the force of repulsion between two protons is equal to the weight of the proton, how far apart are the protons?

5. The force between two point charges is 3.5×10^{-2} N. What is the force if the distance separating the charges is doubled?

6. What equal positive charges would have to be placed on the earth and the moon to neutralize the gravitational force between them?

7. What is the velocity of an electron in the hydrogen atom if the centripetal force is supplied by the coulomb force between the electron and proton? The radius of the electron orbit is 5.29×10^{-11} m.

8. Find the electrical force on an alpha particle when it is 6.00×10^{-11} m from an aluminum nucleus. (*Hint:* find the number of protons in an alpha particle and the number of protons in an aluminum nucleus.)

9. Two identical metal spheres are placed 15.0 cm apart. A charge of 6.00 μC is placed on one sphere, whereas a charge of -2.00 μC is placed on the other. What is the force on each sphere? If the two spheres are brought together and touched and then separated to their original separation, what will be the force on each sphere?

10. Two identical metal spheres attract each other with a force of 5.00×10^{-6} N when they are 5.00 cm apart. The spheres are then touched together and then removed to the original separation where now a force of repulsion of 1.00×10^{-6} N is observed. What is the charge on each sphere after touching and before touching?

11. Two point charges repel each other with a force of 3.00×10^{-5} N when they are 20.0 cm apart. Find the force if the distance is reduced to 5.00 cm.

18.5 Multiple Charges

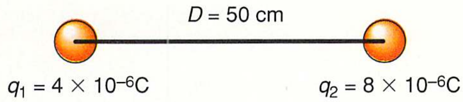
12. How far from a charge $q_1 = 3$ μC should you place a charge of $q_2 = 9$ μC, such that the charge q_2 experiences the force 3.98×10^{-2} N?

13. Three charges $q_1 = 2.00$ μC, $q_2 = 5.00$ μC, and $q_3 = 8.00$ μC are placed along the x-axis at 0.00 cm, 45.0 cm, and 72.4 cm, respectively. Find the force on each charge.

14. Three identical charges $q_1 = q_2 = q_3 = 1.00$ μC are placed along the x-axis at $x = 0$, 0.750, and 2.00 m. What is the magnitude and direction of the resultant force on each charge?

15. Three charges of 2.00 μC, -4.00 μC, and 6.00 μC are placed on the same line, each 15.0 cm apart. Find the resultant force on each charge.

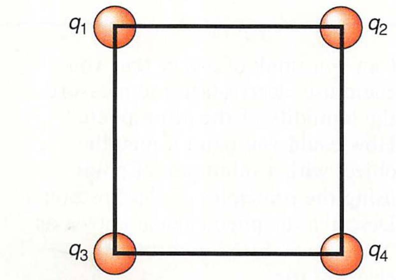
16. Two charges are separated as shown. Where should a third charge be placed on the line between them such that the resultant force on it will be zero? Does it matter if the third charge is positive or negative?



17. Repeat problem 16 but now let charge q_1 be negative, and find any position on the line, either to the left of q_1, between q_1 and q_2, or to the right of q_2, where a third charge can be placed that experiences a zero resultant force.

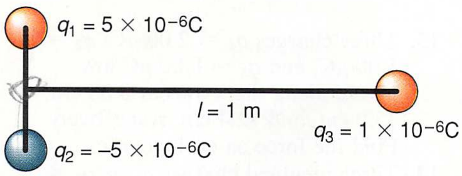
†**18.** Three charges of 2.00 μC, −4.00 μC, and 6.00 μC are placed at the vertices of an equilateral triangle of length 10.0 cm on a side. Find the resultant force on each charge.

†**19.** If q_1 = 5.00 μC = q_2 = q_3 = q_4 are located on the corners of a square of length 20.0 cm, find the resultant force on q_3.

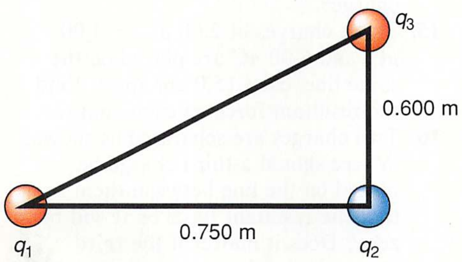


†**20.** Charges of 2.54 μC, −7.86 μC, 5.34 μC, and −3.78 μC are placed on the corners of a square of side 23.5 cm. Find the resultant force on the first charge.

†**21.** Find the force on charge q_3 in the diagram. The distance separating charges q_1 and q_2 is 5.00 cm.

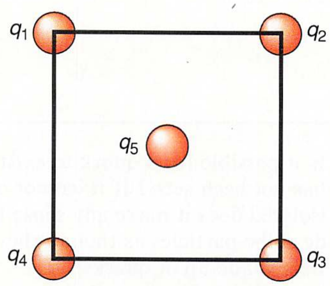


†**22.** Find the resultant force on charge q_3 in the diagram if q_1 = 2.00 μC, q_2 = −7 μC, and q_3 = 5.00 μC.



Additional Problems

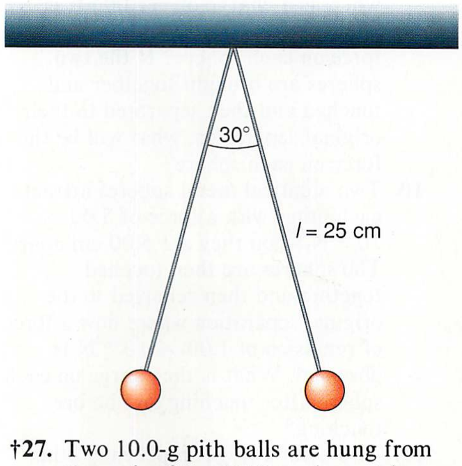
†**23.** Find the force on charge q_5 = 5.00 μC, located at the center of a square 25.0 cm on a side if q_1 = q_2 = 3.00 μC and q_3 = q_4 = 6.00 μC.



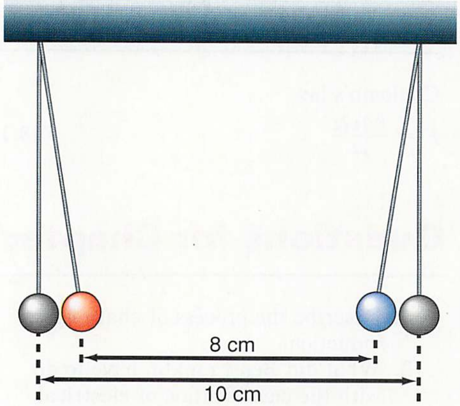
24. Four electrons are located at the corners of a rectangle, 4.00 cm by 3.00 cm, one electron at each corner. Find the magnitude and direction of the net force on each electron due to the other three.

†**25.** Two small, equally charged spheres of mass 0.500 g are suspended from the same point by a silk fiber 50.0 cm long. The repulsion between them keeps them 15.0 cm apart. What is the charge on each sphere?

†**26.** Two pith balls of 10.0-g mass are hung from ends of a string 25.0 cm long, as shown. When the balls are charged with equal amounts of charge, the threads separate to an angle of 30.0°. What is the charge on each ball?

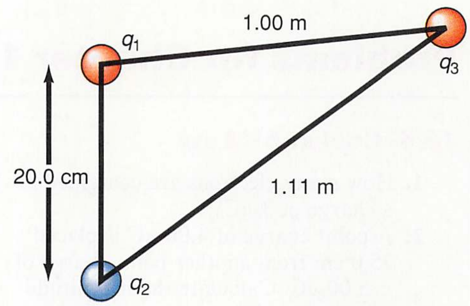


†**27.** Two 10.0-g pith balls are hung from the ends of two 25.0-cm long strings as shown. When an equal and opposite charge is placed on each ball, their separation is reduced from 10.0 cm to 8.00 cm. Find the tension in each string and the charge on each ball.



28. Suppose that equal charges are to be placed on the earth and on a 54.5-kg woman so as to render the woman effectively weightless. How much would the charge on each body have to be?

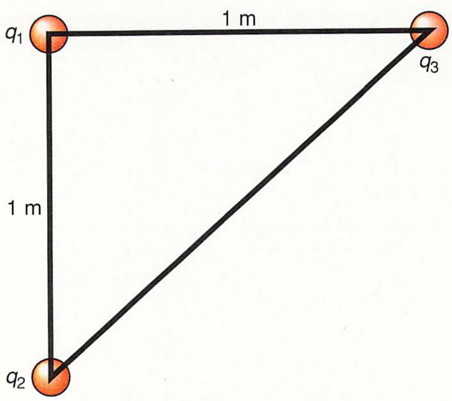
†**29.** Find the force on q_3 in the diagram if q_1 = 8.00 μC, q_2 = −8.00 μC, and q_3 = 8.00 μC.



†**30.** A charge of 15.0 μC is on a metallic sphere 10.0-cm radius. It is then touched to a sphere of 5.00-cm radius, until the surface charge density is the same on both spheres. What is the charge on each sphere after they are separated?

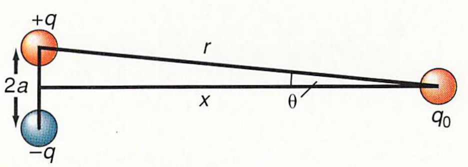
†**31.** Two small spheres carrying charges q_1 = 7.00 μC and q_2 = 5.00 μC are separated by 20.0 cm. If q_2 were free to move, what would its initial acceleration be? Sphere 2 has the mass m_2 = 15.0 g.

†32. Where should a fourth charge, $q_4 = 3.00\ \mu C$, be placed to give a net force of zero on charge q_3? Charges $q_1 = 2.00\ \mu C$, $q_2 = 4.00\ \mu C$, and $q_3 = 2.00\ \mu C$.

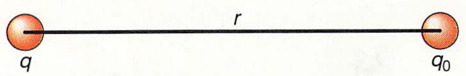


†33. Charge $q_1 = 3.00\ \mu C$ is located at the coordinates (0,2) and charge $q_2 = 6.00\ \mu C$ is located at the coordinates (1,0) of a Cartesian coordinate system. Find the coordinates of a third charge that will experience a zero net force.

†34. The configuration of a positive charge q separated by a distance $2a$ from a negative charge $-q$, is called an electric dipole. Show that the force exerted by an electric dipole on a point charge q_0, located as shown in the diagram varies as $1/r^3$ while the force between a point charge q and the point charge q_0 varies as $1/r^2$. Which force is the weaker?



Dipole and point charge

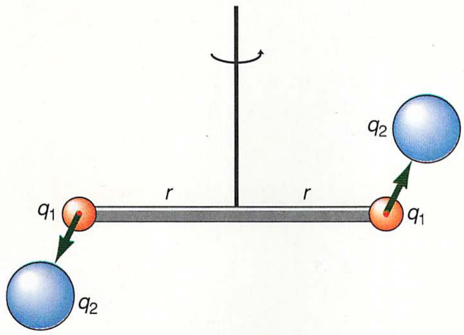


Two point charges

35. A charge of $3.00\ \mu C$ is located at the origin and a charge of $-3.00\ \mu C$ is located on the x-axis at the point $x = 10.0$ cm, forming an electric dipole. Find the force exerted by this dipole on a proton located on the x-axis at the point $x = 40.0$ cm.

36. A charge of $3.00\ \mu C$ is located at the origin and a charge of $-3.00\ \mu C$ is located on the x-axis at the point $x = 10.0$ cm, forming an electric dipole. Find the force exerted by this dipole on a proton located at the point $x = 25.0$ cm and $y = 35.0$ cm.

†37. A plastic rod 50.0 cm long has a charge $+q_1 = 2.00\ \mu C$ at each end. The rod is then hung from a string and placed so that each charge is only 5.00 cm from negative charges $q_2 = -10.0\ \mu C$, as shown in the diagram. Find the torque acting on the string.



38. A 10.0-g object with a $10.0\text{-}\mu C$ charge is suspended from a vertical spring of spring constant 50 N/m. A charge of $-5.00\ \mu C$ is put on the ground directly below the vertical spring. As a result of the presence of the negative charge, the spring stretches by 18.0 cm relative to its equilibrium position before the negatively charged mass was placed below it. Find the distance between the two charged masses in this new equilibrium position. Assume that they are point objects.

†39. A charge of $5.00\ \mu C$ is uniformly distributed over a copper ring 2.00 cm in radius. What force will this ring exert on a point charge of $8.00\ \mu C$ that is placed 3.00 m away from the ring? Indicate what assumptions you make to solve this problem.

†40. A charge of $2.50\ \mu C$ is placed at the center of a hollow sphere of charge of $8.00\ \mu C$. What is the resultant force on the charge placed at the center of the sphere? Indicate what assumptions you make to solve this problem.

Interactive Tutorials

41. Coulomb's law. Two charges $q_1 = 2.00 \times 10^{-6}$ C and $q_2 = 3.00 \times 10^{-6}$ C are separated by a distance $r = 1.00$ m. Calculate the electrostatic force F of repulsion acting on charge 1 as the distance of separation is increased from $r = 1$ to $r = 10$ m. Show how the force F varies with the distance r.

42. Two electrons of charge $q_1 = q_2 = e = 1.60 \times 10^{-19}$ C are positioned at the coordinates (0,1) and (0,−1) (in meters) of a Cartesian coordinate system. Calculate the net force F_3 on an electron q_3 as it is moved from $x = 0$ to $x = 10.0$ m along the x-axis.

43. Coulomb's law and multiple charges. Two charges $q_1 = 8.32 \times 10^6$ C and $q_2 = -2.55 \times 10^6$ C lie on the x-axis and are separated by the distance $r_{12} = 0.823$ m. A third charge $q_3 = 3.87 \times 10^6$ C is located a distance $r_{23} = 0.475$ m from charge q_2, and the line between charge 2 and 3 makes an angle $\phi = 60.0°$ with respect to the x-axis. Find the resultant force on (a) charge 3, (b) charge 2, and (c) charge 1.

44. Coulomb's law and a continuous charge distribution. A rod of charge of length $L = 0.100$ m lies on the x-axis. One end of the rod lies at the origin and the other end is on the positive x-axis. A charge $q' = 7.36 \times 10^{-6}$ C is uniformly distributed over the rod. Find the force exerted on a point charge $q = 2.95 \times 10^{-6}$ C that lies on the x-axis at distance $x_0 = 0.175$ m from the origin of the coordinate system.