Chapter 22

Answer to Checkpoint Questions

1. C and D attract; B and D attract

2. (a) leftward; (b) leftward; (c) leftward

3. (a) a, c, b; (b) less than

4. $-15e$ (net charge of $-30e$ is equally shared)

Answer to Questions

1. No, only for charged particles, charged particle-like objects

2. all tie

3. a and b

4. (a) between; (b) positively charged; (c) unstable

5. two points: one to the left of the particles and one between the protons

6. $2q^2/4\pi\epsilon_0 r^2$, upward

7. $6q^2/4\pi\epsilon_0 d^2$, leftward

8. a and d tie, then b and c tie

9. (a) same; (b) less than; (c) cancel; (d) add; (e) the adding components; (f) positive direction of y; (g) negative direction of y; (h) positive direction of x; (i) negative direction of x

10. (a) positive; (b) negative

11. (a) A, B, and D; (b) all four; (c) connect A and D, disconnect them, then connect one of them to B (there are two other solutions)

12. (a) neutral; (b) negatively

13. (a) possibly; (b) definitely

14. (a) Ground A with the wire, bring the positively charged rod near A but not touching it, remove the wire (A is now negatively charged), remove the rod, connect the wire between A and B (both are now negatively charged by the same amount), remove the wire. (b) Method 1: Connect the two spheres with the wire; bring the rod near sphere A (A now has excess negative charge and B has just as much excess positive charge); remove the wire; remove the rod. Method 2: Ground A with the wire, bring the positively charged rod near A but not touching it, remove the wire (A is now negatively charged), remove the rod, ground B with the wire, bring A near B (A is negatively charged and B is now positively charged by the same amount), remove the wire.

15. same

16. Once enough of the electrons have moved to the opposite end, any other conduction electron is repelled by the electrons at the opposite end as much as it is repelled by the negatively charged rod at the near end.

17. D

18. no (the person and the conductor share the charge)

Solutions to Exercises & Problems

1E

The charge transferred is

$$q = it = (2.5 \times 10^4\,\mathrm{A})(20 \times 10^{-6}\,\mathrm{s}) = 0.50\,\mathrm{C}\,.$$

2E

(a)

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 r^2} = \frac{(1.00\,\mathrm{C})^2(8.99 \times 10^9\,\mathrm{N{\cdot}m^2/C^2})}{(1.00\,\mathrm{m})^2} = 8.99 \times 10^9\,\mathrm{N}\,.$$

(b)

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 r^2} = \frac{(1.00\,\mathrm{C})^2(8.99 \times 10^9\,\mathrm{N{\cdot}m^2/C^2})}{(1.00 \times 10^3\,\mathrm{m})^2} = 8.99 \times 10^3\,\mathrm{N}\,.$$

3E

The magnitude of the force is given by

$$F = \frac{1}{4\pi\epsilon_0}\,\frac{q_1 q_2}{r^2}\,,$$

where q_1 and q_2 are the magnitudes of the charges and r is the distance between them. Thus

$$F = \frac{(8.99 \times 10^9 \ \mathrm{N{\cdot}m^2/C^2})(3.00 \times 10^{-6}\,\mathrm{C})(1.50 \times 10^{-6}\,\mathrm{C})}{(12.0 \times 10^{-2}\,\mathrm{m})^2} = 2.81\,\mathrm{N}\,.$$

4E

The magnitude of the force that either charge exerts on the other is given by

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}\,,$$

where r is the distance between them. Thus

$$\begin{aligned} r &= \sqrt{\frac{q_1 q_2}{4\pi\epsilon_0 F}} \\ &= \sqrt{\frac{(8.99 \times 10^9\,\mathrm{N{\cdot}m^2/C^2})(26.0 \times 10^{-6}\,\mathrm{C})(47.0 \times 10^{-6}\,\mathrm{C})}{5.70\,\mathrm{N}}} = 1.38\,\mathrm{m}\,. \end{aligned}$$

5E

(a) From Newtons's third law $m_1 a_1 = m_2 a_2$, so

$$m_2 = \frac{m_1 a_1}{a_2} = \frac{(6.3 \times 10^{-7}\,\mathrm{kg})(7.0\,\mathrm{m/s^2})}{9.0\,\mathrm{m/s^2}} = 4.9 \times 10^{-7}\,\mathrm{kg}\,.$$

(b) Since $F = q^2/4\pi\epsilon_0 r^2 = m_1 a_1$,

$$\begin{aligned} q &= r\sqrt{4\pi\epsilon_0 m_1 a_1} \\ &= (3.2 \times 10^{-3}\,\mathrm{m})\sqrt{\frac{(6.3 \times 10^{-7}\,\mathrm{kg})(7.0\,\mathrm{m/s^2})}{8.99 \times 10^9\,\mathrm{N{\cdot}m^2/C^2}}} = 7.1 \times 10^{-11}\,\mathrm{C}\,. \end{aligned}$$

6E

Use $|F_{AB}| = |q_A q_B|/(4\pi\epsilon_0 d^2)$, etc.
(a) Since $q_A = -2Q$ and $q_C = +8Q$,

$$|F_{AC}| = \frac{|(-2Q)(+8Q)|}{4\pi\epsilon_0 d^2} = \frac{4Q^2}{\pi\epsilon_0 d^2}\,.$$

After making contact with each other, both A and B now have a charge of $[-2Q + (-4Q)]/2 = -3Q$. When B is grounded its charge is zero. After making contact with

C, which has a charge of $+8Q$, B has a charge of $[0+(-8Q)]/2 = -4Q$, so does charge C. Thus finally $Q_A = -3Q$ and $Q_B = Q_C = -4Q$. Therefore

(b)

$$|F_{AC}| = \frac{|(-3Q)(-4Q)|}{4\pi\epsilon_0 d^2} = \frac{3Q^2}{\pi\epsilon_0 d^2}\,;$$

(c)

$$|F_{BC}| = \frac{|(-4Q)(-4Q)|}{4\pi\epsilon_0 d^2} = \frac{4Q^2}{\pi\epsilon_0 d^2}\,.$$

7E

Let the initial charge on either spheres 1 and 2 be q. After being touched by sphere 3, sphere 1 retains only half of q. After being touched by sphere 3, sphere 2 has $(q+q/2)/2 = 3q/4$ left. So $F' = c(q/2)(3q/4) = (3/8)cq^2 = (3/8)F$, where c is a constant.

8P

Since q_3 is in equilibrium $F_{31} + F_{32} = 0$, i.e.,

$$\frac{1}{4\pi\epsilon_0}\frac{q_1q_3}{(2d)^2} + \frac{1}{4\pi\epsilon_0}\frac{q_2q_3}{d^2} = 0\,,$$

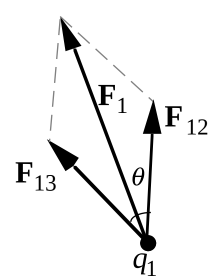
which gives $q_1 = -4q_2$.

9E

(a) The magnitude of the force is

$$F_{12} = \frac{1}{4\pi\epsilon_0}\frac{q_1q_2}{d^2} = (8.99\times10^9\,\mathrm{N\cdot m^2/C^2})\frac{(20.0\times10^{-6}\,\mathrm{C})^2}{(1.50\,\mathrm{m})^2} = 1.60\,\mathrm{N}\,.$$

(b) The magnitude of the force on q_1 now becomes



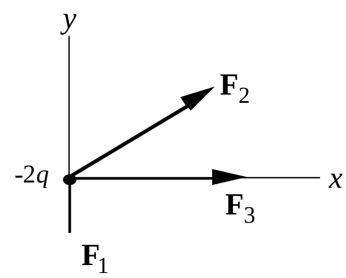
$$\begin{aligned} F_1 &= \sqrt{F_{12}^2 + F_{13}^2 + 2F_{12}F_{13}\cos\theta} \\ &= F_{12}\sqrt{2+2\cos\theta} \\ &= (1.60\,\mathrm{N})\sqrt{2+2\cos 60^\circ} = 2.77\,\mathrm{N}\,, \end{aligned}$$

where we have used $F_{12} = F_{13} = kq_1q_2/d^2 = kq_1q_3/d^2$.

10P

Put the origin of a coordinate system at the lower left corner of the square. Take the y

axis to be vertically upward and the x axis to be horizontal. The force exerted by the charge $+q$ on the charge $-2q$ is



$$\mathbf{F}_1 = \frac{1}{4\pi\epsilon_0}\frac{q(2q)}{a^2}(-\mathbf{j}),$$

the force by the charge $-q$ to $-2q$ is

$$\mathbf{F}_2 = \frac{1}{4\pi\epsilon_0}\frac{(2q)(-q)}{(\sqrt{2}a)^2}\left(-\frac{\mathbf{i}+\mathbf{j}}{\sqrt{2}}\right) = \frac{1}{4\pi\epsilon_0}\frac{q^2}{a^2}\left(\frac{\mathbf{i}}{\sqrt{2}}+\frac{\mathbf{j}}{\sqrt{2}}\right),$$

and the force by the charge $+2q$ to $-2q$ is

$$\mathbf{F}_3 = \frac{1}{4\pi\epsilon_0}\frac{(2q)(-2q)}{a^2}(-\mathbf{i}) = \frac{1}{4\pi\epsilon_0}\frac{4q^2}{a^2}\mathbf{i}.$$

Thus the horizontal (x) component of the resultant force on the charge $-2q$ is

$$\begin{aligned} F_x = F_{1x}+F_{2x}+F_{3x} &= \frac{1}{4\pi\epsilon_0}\frac{q^2}{a^2}\left(\frac{1}{\sqrt{2}}+4\right) \\ &= (8.99\times 10^9\,\mathrm{N\cdot m^2/C^2})\frac{(1.0\times 10^{-7}\,\mathrm{C})^2}{(5.0\times 10^{-2}\,\mathrm{m})^2}\left(\frac{1}{\sqrt{2}}+4\right) = 0.17\,\mathrm{N}, \end{aligned}$$

while the vertical (y) component is

$$F_y = F_{1y}+F_{2y}+F_{3y} = \frac{1}{4\pi\epsilon_0}\frac{q^2}{a^2}\left(-2+\frac{1}{\sqrt{2}}\right) = -0.046\,\mathrm{N}.$$

11P

(a) Let the force F on Q be

$$F = \frac{1}{4\pi\epsilon_0}\left[\frac{q_1Q}{(-a-a/2)^2}+\frac{q_2Q}{(a-a/2)^2}\right] = 0$$

and solve for q_1: $q_1 = 9q_2$.
(b) Now

$$F = \frac{1}{4\pi\epsilon_0}\left[\frac{q_1Q}{(-a-3a/2)^2}+\frac{q_2Q}{(a-3a/2)^2}\right] = 0,$$

which gives $q_1 = -25q_2$.

12P

Let the two charges be q_1 and q_2. Then $q_1 + q_2 = 5.0 \times 10^{-5}\,\mathrm{C}$. Also $F_{12} = q_1 q_2 / 4\pi\epsilon_0 r^2$, i.e.,

$$1.0\,\mathrm{N} = \frac{q_1 q_2 (8.99 \times 10^9\,\mathrm{N\cdot m^2/C^2})}{(2.0\,\mathrm{m})^2}\,.$$

Solve for q_1 and q_2: $q_1,\, q_2 = 1.2 \times 10^{-5}\,\mathrm{C}$ and $3.8 \times 10^{-5}\,\mathrm{C}$.

13P

Assume the charge distributions are spherically symmetric so Coulomb's law can be used. Let q_1 and q_2 be the original charges and choose the coordinate system so the force on q_2 is positive if it is repelled by q_1. Take the distance between the charges to be r. Then the force on q_2 is

$$F_a = -\frac{1}{4\pi\epsilon_0}\,\frac{q_1 q_2}{r^2}\,.$$

The negative sign indicates that the spheres attract each other.

After the wire is connected the spheres, being identical, have the same charge. Since charge is conserved the total charge is the same as it was originally. This means the charge on each sphere is $(q_1 + q_2)/2$. The force is now one of repulsion and is given by

$$F_b = \frac{1}{4\pi\epsilon_0}\,\frac{(q_1 + q_2)^2}{4r^2}\,.$$

Solve the two force equations simultaneously for q_1 and q_2. The first gives

$$q_1 q_2 = -4\pi\epsilon_0 r^2 F_a = \frac{(0.500\,\mathrm{m})^2 (0.108\,\mathrm{N})}{8.99 \times 10^9\,\mathrm{N\cdot m^2\,/C^2}} = -3.00 \times 10^{-12}\,\mathrm{C^2}$$

and the second gives

$$q_1 + q_2 = r\sqrt{4(4\pi\epsilon_0)F_b} = (0.500\,\mathrm{m})\sqrt{\frac{4(0.0360\,\mathrm{N})}{8.99 \times 10^9\,\mathrm{N\cdot m^2\,/C^2}}} = 2.00 \times 10^{-6}\,\mathrm{C}\,.$$

Thus

$$q_2 = \frac{-(3.00 \times 10^{-12}\,\mathrm{C^2})}{q_1}$$

and

$$q_1 - \frac{3.00 \times 10^{-12}\,\mathrm{C^2}}{q_1} = 2.00 \times 10^{-6}\,\mathrm{C}\,.$$

Multiply by q_1 to obtain the quadratic equation

$$q_1^2 - (2.00 \times 10^{-6}\,\mathrm{C})q_1 - 3.00 \times 10^{-12}\,\mathrm{C^2} = 0\,.$$

The solutions are

$$q_1 = \frac{-2.00\times10^{-6}\,\mathrm{C} \pm \sqrt{(2.00\times10^{-6}\,\mathrm{C})^2 + 4(3.00\times10^{-12}\,\mathrm{C}^2)}}{2}\,.$$

If the plus sign is used $q_1 = 1.00\times10^{-6}$ C and if the minus sign is used $q_1 = -3.00\times10^{-6}$ C. Use $q_2 = (-3.00\times10^{-12})/q_1$ to calculate q_2. If $q_1 = 1.00\times10^{-6}$ C then $q_2 = -3.00\times10^{-6}$ C and if $q_1 = -3.00\times10^{-6}$ C then $q_2 = 1.00\times10^{-6}$ C. Since the spheres are identical the solutions are essentially the same: one sphere originally had charge 1.00×10^{-6} C and the other had charge -3.00×10^{-6} C.

Another solution exists. If the signs of the charges are reversed the forces remain the same, so a charge of -1.00×10^{-6} C on one sphere and a charge of 3.00×10^{-6} C on the other also satisfies the conditions of the problem.

14P

Let the third charge q_3 be located on the line joining the two charges, a distance x from $q_1 = 1.0\mu$C. Then the net force exerted on q_3 is

$$F_3 = \frac{q_3}{4\pi\epsilon_0}\left[\frac{q_1}{x^2} + \frac{q_2}{(r-x)^2}\right] = 0\,.$$

Substitute $q_1 = +1.0\mu$C, $q_2 = -3.0\mu$C and $r = 10\,$cm into the above equation and solve for x to obtain $x = 14\,$cm.

15P

(*a*)

$$\begin{aligned} F_{21} &= \frac{1}{4\pi\epsilon_0}\frac{|q_1q_2|}{r_{12}^2} = \frac{1}{4\pi\epsilon_0}\frac{|q_1q_2|}{(x_2-x_1)^2+(y_2-y_1)^2} \\ &= \frac{(8.99\times10^9\,\mathrm{N\cdot m^2/C^2})|(3.0\times10^{-6}\,\mathrm{C})(-4.0\times10^{-6}\,\mathrm{C})|}{[(-2.0-3.5)^2+(1.5-0.5)^2](10^{-4}\,\mathrm{m}^2)} \\ &= 36\,\mathrm{N}\,. \end{aligned}$$

The direction of $\mathbf{F}_{21}$ is such that it makes an angle θ with the positive x axis, where

$$\theta = \tan^{-1}\left(\frac{y_2-y_1}{x_2-x_1}\right) = \tan^{-1}\left(\frac{1.5\,\mathrm{cm}-0.5\,\mathrm{cm}}{-2.0\,\mathrm{cm}-3.5\,\mathrm{cm}}\right) = -10^\circ\,.$$

(*b*) Let the third charge be located at (x_3, y_3), a distance r from q_2. Since q_1, q_2 and q_3 must be on the same line, we have $x_3 = x_2 - r\cos\theta$ and $y_3 = y_2 - r\sin\theta$. The force on q_2 exerted by q_3 is $F_{23} = q_2q_3/4\pi\epsilon_0 r^2$, which must cancel with the force exerted by q_1 on q_2:

$$F_{23} = \frac{|q_2q_3|}{4\pi\epsilon_0 r^2} = F_{21}\,,$$

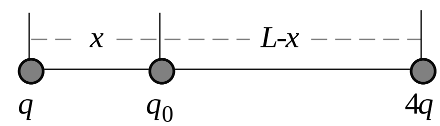
which gives

$$r = \sqrt{\frac{|q_2 q_3|}{4\pi\epsilon_0 F_{12}}} = \sqrt{\frac{(4.0\times10^{-6}\,\mathrm{C})(4.0\times10^{-6}\,\mathrm{C})(8.99\times10^{9}\,\mathrm{N\cdot m^2/C^2})}{36\,\mathrm{N}}} = 6.3\,\mathrm{cm}\,.$$

So $x_3 = x_2 - r\cos\theta = -2.0\,\mathrm{cm} - (6.3\,\mathrm{cm})\cos(-10^\circ) = -8.3\,\mathrm{cm}$ and $y_3 = y_2 - r\sin\theta = 1.5\,\mathrm{cm} - (6.3\,\mathrm{cm})\sin(-10^\circ) = 2.6\,\mathrm{cm}$.

16P

(*a*) If the system of three charges is to be in equilibrium the force on each charge must be zero. Let the third charge be q_0. It must lie between the other two or else the forces acting on it due to the other charges would be in the same direction and q_0 could not be in equilibrium. Suppose q_0 is a distance x from q, as shown on the diagram to the right. The force acting on q_0 is then given by



$$F_0 = \frac{1}{4\pi\epsilon_0}\left[\frac{qq_0}{x^2} - \frac{4qq_0}{(L-x)^2}\right] = 0\,,$$

where the positive direction was taken to be toward the right. Solve this equation for x. Canceling common factors yields $1/x^2 = 4/(L-x)^2$ and taking the square root yields $1/x = 2/(L-x)$. The solution is $x = L/3$.

The force on q is

$$F_q = \frac{1}{4\pi\epsilon_0}\left(\frac{qq_0}{x^2} + \frac{4q^2}{L^2}\right) = 0\,.$$

Solve for q_0: $q_0 = -4qx^2/L^2 = -(4/9)q$, where $x = L/3$ was used.

The force on $4q$ is

$$\begin{aligned} F_{4q} &= \frac{1}{4\pi\epsilon_0}\left[\frac{4q^2}{L^2} + \frac{4qq_0}{(L-x)^2}\right] = \frac{1}{4\pi\epsilon_0}\left[\frac{4q^2}{L^2} + \frac{4(-4/9)q^2}{(4/9)L^2}\right] \\ &= \frac{1}{4\pi\epsilon_0}\left(\frac{4q^2}{L^2} - \frac{4q^2}{L^2}\right) = 0\,. \end{aligned}$$

With $q_0 = -(4/9)q$ and $x = L/3$ all three charges are in equilibrium.

(*b*) If q_0 moves toward q the force of attraction exerted by q is greater in magnitude than the force of attraction exerted by $4q$ and q_0 continues to move toward q and away from its initial position. The equilibrium is unstable.

17P

(*a*) The magnitudes of the gravitational and electrical forces must be the same:

$$\frac{1}{4\pi\epsilon_0}\frac{q^2}{d_{em}^2} = G\,\frac{M_m M_e}{d_{em}^2}\,,$$

where q is the charge on either body, d_{em} is the center-to-center separation of the Earth and Moon, G is the universal gravitational constant, M_e is the mass of the Earth, and M_m is the mass of the Moon. Solve for q:

$$q = \sqrt{4\pi\epsilon_0 G M_m M_e}\,.$$

According the text, $M_e = 5.98 \times 10^{24}$ kg, and $M_m = 7.36 \times 10^{22}$ kg, so

$$\begin{aligned} q &= \sqrt{\frac{(6.67 \times 10^{-11}\,\mathrm{N{\cdot}m^2/kg^2})(7.36 \times 10^{22}\,\mathrm{kg})(5.98 \times 10^{24}\,\mathrm{kg})}{8.99 \times 10^{9}\,\mathrm{N{\cdot}m^2/C^2}}} \\ &= 5.7 \times 10^{13}\,\mathrm{C}\,. \end{aligned}$$

Notice that the distance r cancels because both the electric and gravitational forces are proportional to $1/r^2$.
(b) The charge on a hydrogen ion is $e = 1.60 \times 10^{-19}$ C so there must be

$$\frac{q}{e} = \frac{5.7 \times 10^{13}\,\mathrm{C}}{1.6 \times 10^{-19}\,\mathrm{C}} = 3.6 \times 10^{32}\,\mathrm{ions}\,.$$

Each ion has a mass of 1.67×10^{-27} kg so the total mass needed is

$$(3.6 \times 10^{32})(1.67 \times 10^{-27}\,\mathrm{kg}) = 6.0 \times 10^{5}\,\mathrm{kg}\,.$$

18P

The magnitude of the force of either of the charges on the other is given by

$$F = \frac{1}{4\pi\epsilon_0}\frac{q(Q-q)}{r^2}\,,$$

where r is the distance between the charges. You want the value of q that maximizes the function $f(q) = q(Q-q)$. Set the derivative df/dq equal to zero. This yields $2q - Q = 0$, or $q = Q/2$.

19P

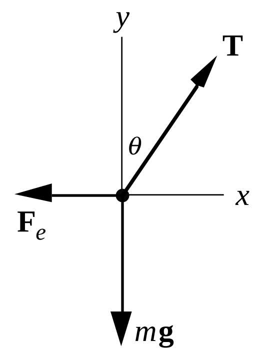
(a) Let the side length of the square be a. Then the magnitude of the force on each charge Q is

$$F_Q = \frac{1}{4\pi\epsilon_0}\left[\frac{\sqrt{2}Qq}{a^2} + \frac{Q^2}{(\sqrt{2}a)^2}\right].$$

Let $F_Q = 0$, we get $Q = -2\sqrt{2}q$.
(b) For both F_Q and F_q to vanish we would require $Q = -2\sqrt{2}q$ and $q = -2\sqrt{2}Q$. These two equations cannot be simultaneously valid unless $Q = q = 0$. So this is impossible.

20P

(a) A force diagram for one of the balls is shown to the right. The force of gravity mg acts downward, the electrical force F_e of the other ball acts to the left, and the tension in the thread acts along the thread, at the angle θ to the vertical. The ball is in equilibrium, so its acceleration is zero. The y component of Newtons second law yields $T\cos\theta - mg = 0$ and the x component yields $T\sin\theta - F_e = 0$. Solve the first equation for T ($T = mg/\cos\theta$) and substitute the result into the second to obtain $mg\tan\theta - F_e = 0$. Now



$$\tan\theta = \frac{x/2}{\sqrt{L^2 - (x/2)^2}}\,.$$

If L is much larger than x we may neglect $x/2$ in the denominator and write $\tan\theta \approx x/2L$. This is equivalent to approximating $\tan\theta$ by $\sin\theta$. The magnitude of the electrical force of one ball on the other is

$$F_e = \frac{q^2}{4\pi\epsilon_0 x^2}\,.$$

When these two substitutions are made in the equation $mg\tan\theta = F_e$, it becomes

$$\frac{mgx}{2L} = \frac{1}{4\pi\epsilon_0}\frac{q^2}{x^2}\,,$$

so

$$x^3 = \frac{1}{4\pi\epsilon_0}\frac{2q^2L}{mg}\,,$$

and

$$x = \left(\frac{q^2L}{2\pi\epsilon_0 mg}\right)^{1/3}\,.$$

(b) Solve $x^3 = (1/4\pi\epsilon_0)(2q^2L/mg)$ for q:

$$q = \pm\sqrt{\frac{4\pi\epsilon_0 mgx^3}{2L}} = \pm\sqrt{\frac{(0.010\,\mathrm{kg})(9.8\,\mathrm{m/s^2})(0.050\,\mathrm{m})^3}{2(8.99\times10^9\,\mathrm{N\cdot m^2/C^2})(1.20\,\mathrm{m})}} = \pm2.4\times10^{-8}\,\mathrm{C}\,.$$

21P

If one of them is discharged, there would no electrostatic repulsion between the two balls and they would both come to the position $\theta = 0$, making contact with each other. A redistribution of charges would then occur, with each of the balls getting $q/2$. They would then again be separated due to electrostatic repulsion, which results in the new separation

$$x' = \left[\frac{(q/2)^2 L}{2\pi\epsilon_0 mg}\right]^{1/3} = \left(\frac{1}{4}\right)^{1/3} x = \left(\frac{1}{4}\right)^{1/3} (5.0\,\text{cm}) = 3.1\,\text{cm}\,.$$

22P

(*a*) Since the rod is in equilibrium the net force acting on it is zero and the net torque about any point is also zero. Write an expression for the net torque about the bearing, equate it to zero, and solve for x. The charge Q on the left exerts an upward force of magnitude $(1/4\pi\epsilon_0)(qQ/h^2)$, at a distance $L/2$ from the bearing. Take the torque to be positive. The attached weight exerts a downward force of magnitude W, at a distance $L/2 - x$ from the bearing. This torque is positive. The charge Q on the right exerts an upward force of magnitude $(1/4\pi\epsilon_0)(2qQ/h^2)$, at a distance $L/2$ from the bearing. This torque is negative. The equation for rotational equilibrium is

$$\frac{1}{4\pi\epsilon_0}\frac{qQ}{h^2}\frac{L}{2} + W\left(\frac{L}{2} - x\right) - \frac{1}{4\pi\epsilon_0}\frac{2qQ}{h^2}\frac{L}{2} = 0\,.$$

The solution for x is

$$x = \frac{L}{2}\left(1 + \frac{1}{4\pi\epsilon_0}\frac{qQ}{h^2 W}\right)\,.$$

(*b*) The net force on the rod vanishes. If N is the magnitude of the upward force exerted by the bearing then

$$W - \frac{1}{4\pi\epsilon_0}\frac{qQ}{h^2} - \frac{1}{4\pi\epsilon_0}\frac{2qQ}{h^2} - N = 0\,.$$

Solve for h so that $N = 0$. The result is

$$h = \sqrt{\frac{1}{4\pi\epsilon_0}\frac{3qQ}{W}}\,.$$

23E

The magnitude of the force is

$$F = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2} = (8.99\times10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)\frac{(1.60\times10^{-19}\,\text{C})^2}{(2.82\times10^{-10}\,\text{m})^2} = 2.89\times10^{-9}\,\text{N}\,.$$

24E

$$F = \frac{q^2}{4\pi\epsilon_0 r^2} = \frac{(-e/3)^2}{4\pi\epsilon_0 r^2} = \frac{(8.99\times10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(1.60\times10^{-19}\,\text{C})^2}{9(2.6\times10^{-15}\,\text{m})^2} = 3.8\,\text{N}\,.$$

25E

The mass of an electron is $m_e = 9.11 \times 10^{-31}\,\mathrm{kg}$ so the number of electrons in a collection with total mass $M = 75.0\,\mathrm{kg}$ is

$$N = \frac{M}{m_e} = \frac{75.0\,\mathrm{kg}}{9.11 \times 10^{-31}\,\mathrm{kg}} = 8.23 \times 10^{31}\,\mathrm{electrons}\,.$$

The total charge of the collection is $q = -Ne = -(8.23 \times 10^{31})(1.60 \times 10^{-19}\,\mathrm{C}) = -1.32 \times 10^{13}\,\mathrm{C}$.

26E

$$Q = N_A q = (6.02 \times 10^{23})(2)(1.60 \times 10^{-19}\,\mathrm{C}) = 1.9 \times 10^5\,\mathrm{C} = 0.19\,\mathrm{MC}\,.$$

27E

(*a*) The magnitude of the force between the ions is given by

$$F = \frac{q^2}{4\pi\epsilon_0 r^2}\,,$$

where q is the charge on either of them and r is the distance between them. Solve for the charge:

$$q = r\sqrt{4\pi\epsilon_0 F} = (5.0 \times 10^{-10}\,\mathrm{m})\sqrt{\frac{3.7 \times 10^{-9}\,\mathrm{N}}{8.99 \times 10^9\,\mathrm{N{\cdot}m^2/C^2}}} = 3.2 \times 10^{-19}\,\mathrm{C}\,.$$

(*b*) Let N be the number of electrons missing from each ion. Then $Ne = q$, or

$$N = \frac{q}{e} = \frac{3.2 \times 10^{-19}\,\mathrm{C}}{1.60 \times 10^{-19}\,\mathrm{C}} = 2\,.$$

28E

(*a*) the number of electrons to be removed is

$$n = \frac{q}{e} = \frac{1.0 \times 10^{-7}\,\mathrm{C}}{1.60 \times 10^{-19}\,\mathrm{C}} = 6.3 \times 10^{11}.$$

(*b*) The fraction is

$$\mathrm{frac} = \frac{n}{NZ} = \frac{6.3 \times 10^{11}}{(2.95 \times 10^{22})(29)} = 7.4 \times 10^{-13}.$$

29E

(a) The magnitude of the force is given by

$$F = \frac{q^2}{4\pi\epsilon_0 r^2}\,,$$

where q is the magnitude of the charge on each drop and r is the center-to-center separation of the drops. Thus

$$F = \frac{(8.99\times10^9\,\mathrm{N\cdot m^2/C^2})(1.00\times10^{-16}\,\mathrm{C})^2}{(1.00\times10^{-2}\,\mathrm{m})^2} = 8.99\times10^{-19}\,\mathrm{N}\,.$$

(b) If N is the number of excess electrons (of charge $-e$ each) on each drop then

$$N = -\frac{q}{e} = -\frac{-1.00\times10^{-16}\,\mathrm{C}}{1.60\times10^{-19}\,\mathrm{C}} = 625\,.$$

30E

Let $q^2/4\pi\epsilon_0 r^2 = mg$, we get

$$r = q\sqrt{\frac{1}{4\pi\epsilon_0 mg}} = (1.60\times10^{-19}\,\mathrm{C})\sqrt{\frac{8.99\times10^9\,\mathrm{N\cdot m^2/C^2}}{(1.67\times10^{-27}\,\mathrm{kg})(9.8\,\mathrm{m/s^2})}} = 0.119\,\mathrm{m}\,.$$

31E

The second electron must be placed a distance d under the first one to produce an upward force that balances the weight of the first one. So

$$W = m_e g = \frac{1}{4\pi\epsilon_0}\frac{e^2}{d^2},$$

which gives

$$d = e\sqrt{\frac{1}{4\pi\epsilon_0}\frac{1}{m_e g}} = (1.6\times10^{-19}\,\mathrm{C})\sqrt{\frac{8.99\times10^9\,\mathrm{N\cdot m^2/C^2}}{(9.11\times10^{-31}\,\mathrm{kg})(9.80\,\mathrm{m/s^2})}} = 5.1\,\mathrm{m}\,.$$

32P

The current intercepted would be

$$i = (4\pi R^2)\left(\frac{\Delta q}{\Delta t}\right) = 4\pi(6.37\times10^6\,\mathrm{m})^2(1500/\,\mathrm{s})(1.6\times10^{-19}\,\mathrm{C}) = 0.122\,\mathrm{A}\,.$$

33P

If charge of magnitude q passes through the lamp in time t the current is $i = q/t$. The charge is the total charge on one mole of electrons, or $q = N_A e$, where N_A is the Avogadro constant. Thus $i = N_A e/t$, or

$$t = \frac{N_A e}{i} = \frac{(6.02 \times 10^{23})(1.60 \times 10^{-19}\,\text{C})}{0.83\,\text{A}} = 1.2 \times 10^5\,\text{s}\,.$$

This is equivalent to 1.3 da.

34P

The numer of moles of H_2O molecules in a glass of water (of volume V) is $n = \rho V/M$, where ρ is the density of water and M is its molar mass. Each H_2O molecule has 10 protons. Thus

$$\begin{aligned} Q &= 10enN_A = \frac{10e\rho V N_A}{M} \\ &= \frac{10(1.6 \times 10^{-19}\,\text{C})(1.00 \times 10^3\,\text{kg/m}^3)(250 \times 10^{-6}\,\text{m}^3)(6.02 \times 10^{23}/\,\text{mol})}{1.8 \times 10^{-2}\,\text{kg/mol}} \\ &= 1.3 \times 10^7\,\text{C}\,. \end{aligned}$$

35P

(a) Every cesium ion at a corner of the cube exerts a force of the same magnitude on the chlorine ion at the cube center. Each force is a force of attraction and is directed toward the cesium ion that exerts it, along the body diagonal of the cube. We can pair every cesium ion with another, diametrically positioned at the opposite corner of the cube. Since the two ions in such a pair exerts forces that have the same magnitude but are oppositely directed, the two forces sum to zero and, since every cesium ion can be paired in this way, the total force on the chlorine ion is zero.

(b) Rather than remove a cesium ion, superpose charge $-e$ at the position of one cesium ion. This neutralizes the ion and, as far as the electrical force on the chlorine ion is concerned, it is equivalent to removing the ion. The forces of the 8 cesium ions at the cube corners sum to zero, so the only force on the chlorine ion is the force of the added charge.

The length of a body diagonal of a cube is $\sqrt{3}a$, where a is the length of a cube edge. Thus the distance from the center of the cube to a corner is $d = (\sqrt{3}/2)a$. The force has magnitude

$$\begin{aligned} F &= \frac{1}{4\pi\epsilon_0}\frac{e^2}{d^2} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{(3/4)a^2} \\ &= \frac{(8.99 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(1.60 \times 10^{-19}\,\text{C})^2}{(3/4)(0.40 \times 10^{-9}\,\text{m})^2} = 1.9 \times 10^{-9}\,\text{N}\,. \end{aligned}$$

Since both the added charge and the chlorine ion are negative the force is one of repulsion. The chlorine ion is pushed away from the site of the missing cesium ion.

36P

In this case the net charge on each penny would be $q_{\rm net} = \eta q$, where $q = 137000\,{\rm C}$ and $\eta = 0.00010\%$. The force is then

$$F = \frac{q_{\rm net}^2}{4\pi\epsilon_0 r^2} = \frac{[(0.00010\%)(137000\,{\rm C})]^2(8.99\times10^9\,{\rm N{\cdot}m^2/C^2})}{(1.0\,{\rm m})^2} = 1.7\times10^8\,{\rm N}\,.$$

Therefore the magnitudes of the positive charge on the proton and negative charge on the electron cannot possibly differ by as much as 0.00010%.

37P

The net charge carried by John whose mass is m is roughly

$$\begin{aligned} q &= (0.01\%)\frac{mN_AZ_e}{M} \\ &= (0.01\%)\frac{(200\,{\rm lb})(0.4536\,{\rm kg/lb})(6.02\times10^{23}/\,{\rm mol})(18)(1.6\times10^{-19}\,{\rm C})}{0.018\,{\rm kg/mol}} \\ &= 9\times10^5\,{\rm C}\,, \end{aligned}$$

and the net charge carried by Mary is half of that. So the electrostatic force between them is estimated to be

$$F \approx \frac{1}{4\pi\epsilon_0}\frac{q(q/2)}{d^2} = (8.99\times10^9\,{\rm N{\cdot}m^2/C^2})\frac{(9\times10^5\,{\rm C})^2}{2(30\,{\rm m})^2} = 4\times10^{18}\,{\rm N}\,.$$

38E

Apply the principle of charge conservation. The results are:
(a) an electron;
(b) a proton.

39E

None of the reactions given include a beta decay, so the number of protons, the number of neutrons, and the number of electrons are each conserved. Atomic numbers (numbers of protons and numbers of electrons) and molar masses (combined numbers of protons and neutrons) can be found in Appendix F of the text.

(a) ^{1}H has 1 proton, 1 electron, and 0 neutrons and ^{9}Be has 4 protons, 4 electrons, and $9-4=5$ neutrons, so X has $1+4=5$ protons, $1+4=5$ electrons, and $0+5-1=4$ neutrons. One of the neutrons is freed in the reaction. X must be boron with a molar mass of $5+4=9\,{\rm g/\,mol}$: ^{9}B.

(*b*) ^{12}C has 6 protons, 6 electrons, and $12-6=6$ neutrons and ^{1}H has 1 proton, 1 electron, and 0 neutrons, so X has $6+1=7$ protons, $6+1=7$ electrons, and $6+0=6$ neutrons. It must be nitrogen with a molar mass of $7+6=13\,\mathrm{g/mol}$: ^{13}N.

(*c*) ^{15}N has 7 protons, 7 electrons, and $15-7=8$ neutrons; ^{1}H has 1 proton, 1 electron, and 0 neutrons; and ^{4}He has 2 protons, 2 electrons, and $4-2=2$ neutrons; so X has $7+1-2=6$ protons, 6 electrons, and $8+0-2=6$ neutrons. It must be carbon with a molar mass of $6+6=12$: ^{12}C.

40E

(*a*)

$$F=\frac{1}{4\pi\epsilon_0}\frac{q^2}{r^2}=\frac{(8.99\times10^{9}\,\mathrm{N\cdot m^2/C^2})[2(1.60\times10^{-19}\,\mathrm{C})]^2}{(9.0\times10^{-15}\,\mathrm{m})^2}=11\,\mathrm{N}\,.$$

(*b*)

$$a=\frac{F}{m}=\frac{11\,\mathrm{N}}{4(1.60\times10^{-27}\,\mathrm{kg})}=1.7\times10^{27}\,\mathrm{m/s^2}\,.$$

41

(*a*) $F=(Q^2/4\pi\epsilon_0 d^2)\alpha(1-\alpha)$;
(*c*) 0.5;
(*d*) 0.15 and 0.85

42

(*a*) Let $J=qQ/4\pi\epsilon_0 d^2$. For $\alpha<0$, $F=-J[1/\alpha^2+1/(1+|\alpha|)^2]$; for $0<\alpha<1$, $F=J[1/\alpha^2-1/(1-\alpha)^2]$; for $1<\alpha$, $F=J[1/\alpha^2+1/(\alpha-1)^2]$