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tered on the same line. For three situations, the uniform charges on rings *A* and *B* are, respectively, (1) q_0 and q_0 , (2) $-q_0$ and $-q_0$, and (3) $-q_0$ and q_0 . Rank the situations according to the magnitude of the net electric field at (a) point P_1 midway between the rings, (b) point P_2 at the center of ring *B*, and (c) point P_3 to the right of ring *B*, greatest first.

7 The potential energies associated with four orientations of an electric dipole in an electric field are (1) $-5U_0$, (2) $-7U_0$, (3) $3U_0$, and (4) $5U_0$, where U_0 is positive. Rank the orientations according to (a) the angle between the electric dipole moment \vec{p} and the electric field \vec{E} and (b) the magnitude of the torque on the electric dipole, greatest first.

8 (a) In the Checkpoint of Section 22-9, if the dipole rotates from orientation 1 to orientation 2, is the work done on the dipole by the field positive, negative, or zero? (b) If, instead, the dipole rotates from orientation 1 to orientation 4, is the work done by the field more than, less than, or the same as in (a)?

9 Figure 22-26 shows two disks and a flat ring, each with the same uniform charge Q . Rank the objects according to the magnitude of the electric field they create at points *P* (which are at the same vertical heights), greatest first.

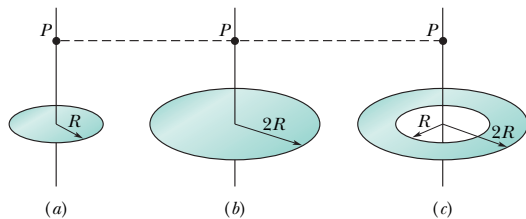


Fig. 22-26 Question 9.

10 In Fig. 22-27, an electron *e* travels through a small hole in plate *A* and then toward plate *B*. A uniform electric field in the region between the plates then slows the electron without deflecting

it. (a) What is the direction of the field? (b) Four other particles similarly travel through small holes in either plate *A* or plate *B* and then into the region between the plates. Three have charges $+q_1$, $+q_2$, and $-q_3$. The fourth (labeled *n*) is a neutron, which is electrically neutral. Does the speed of each of those four other particles increase, decrease, or remain the same in the region between the plates?

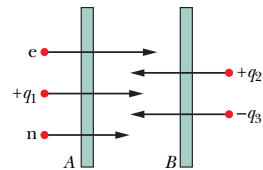


Fig. 22-27 Question 10.

11 In Fig. 22-28*a*, a circular plastic rod with uniform charge $+Q$ produces an electric field of magnitude E at the center of curvature (at the origin). In Figs. 22-28*b*, *c*, and *d*, more circular rods, each with identical uniform charges $+Q$, are added until the circle is complete. A fifth arrangement (which would be labeled *e*) is like that in *d* except the rod in the fourth quadrant has charge $-Q$. Rank the five arrangements according to the magnitude of the electric field at the center of curvature, greatest first.

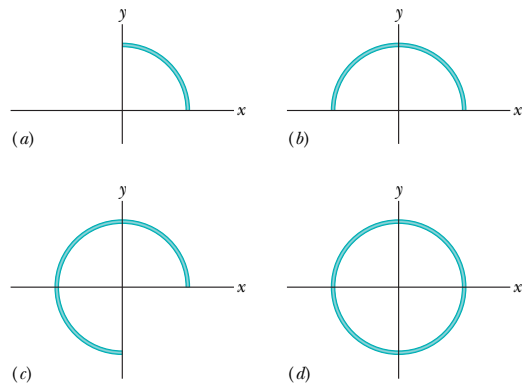


Fig. 22-28 Question 11.

PROBLEMS

GO Tutoring problem available (at instructor's discretion) in WileyPLUS and WebAssign
SSM Worked-out solution available in Student Solutions Manual **WWW** Worked-out solution is at <http://www.wiley.com/college/halliday>
 ••• Number of dots indicates level of problem difficulty **ILW** Interactive solution is at <http://www.wiley.com/college/halliday>
 Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com

sec. 22-3 Electric Field Lines

•1 Sketch qualitatively the electric field lines both between and outside two concentric conducting spherical shells when a uniform positive charge q_1 is on the inner shell and a uniform negative charge $-q_2$ is on the outer. Consider the cases $q_1 > q_2$, $q_1 = q_2$, and $q_1 < q_2$.

•2 In Fig. 22-29 the electric field lines on the left have twice the separation of those on the right. (a) If the magnitude of the field at *A* is 40 N/C, what is the magnitude of the force on a proton at *A*? (b) What is the magnitude of the field at *B*?

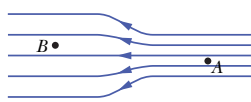


Fig. 22-29 Problem 2.

sec. 22-4 The Electric Field Due to a Point Charge

•3 SSM The nucleus of a plutonium-239 atom contains 94 protons. Assume that the nucleus is a sphere with radius 6.64 fm and with the charge of the protons uniformly spread through the sphere. At the nucleus surface, what are the (a) magnitude and (b) direction (radially inward or outward) of the electric field produced by the protons?

•4 Two particles are attached to an *x* axis: particle 1 of charge -2.00×10^{-7} C at $x = 6.00$ cm, particle 2 of charge $+2.00 \times 10^{-7}$ C at $x = 21.0$ cm. Midway between the particles, what is their net electric field in unit-vector notation?

•5 SSM What is the magnitude of a point charge whose electric field 50 cm away has the magnitude 2.0 N/C?

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•6 What is the magnitude of a point charge that would create an electric field of 1.00 N/C at points 1.00 m away?

••7 **SSM ILW WWW** In Fig. 22-30, the four particles form a square of edge length $a = 5.00$ cm and have charges $q_1 = +10.0$ nC, $q_2 = -20.0$ nC, $q_3 = +20.0$ nC, and $q_4 = -10.0$ nC. In unit-vector notation, what net electric field do the particles produce at the square's center?

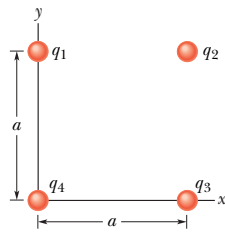


Fig. 22-30 Problem 7.

••8 **GO** In Fig. 22-31, the four particles are fixed in place and have charges $q_1 = q_2 = +5e$, $q_3 = +3e$, and $q_4 = -12e$. Distance $d = 5.0$ μm . What is the magnitude of the net electric field at point P due to the particles?

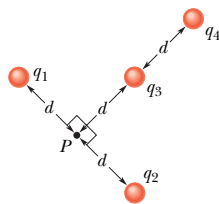


Fig. 22-31 Problem 8.

••9 **GO** Figure 22-32 shows two charged particles on an x axis: $-q = -3.20 \times 10^{-19}$ C at $x = -3.00$ m and $q = 3.20 \times 10^{-19}$ C at $x = +3.00$ m. What are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the net electric field produced at point P at $y = 4.00$ m?

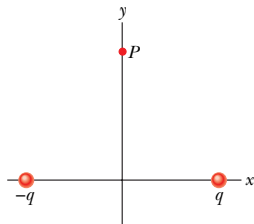


Fig. 22-32 Problem 9.

••10 **GO** Figure 22-33a shows two charged particles fixed in place on an x axis with separation L . The ratio q_1/q_2 of their charge magnitudes is 4.00. Figure 22-33b shows the x component $E_{\text{net},x}$ of their net electric field along the x axis just to the right of particle 2. The x axis scale is set by $x_s = 30.0$ cm. (a) At what value of $x > 0$ is $E_{\text{net},x}$ maximum? (b) If particle 2 has charge $-q_2 = -3e$, what is the value of that maximum?

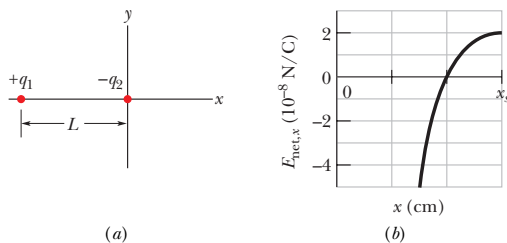


Fig. 22-33 Problem 10.

••11 **SSM** Two particles are fixed to an x axis: particle 1 of charge $q_1 = 2.1 \times 10^{-8}$ C at $x = 20$ cm and particle 2 of charge $q_2 =$

$-4.00q_1$ at $x = 70$ cm. At what coordinate on the axis is the net electric field produced by the particles equal to zero?

••12 **GO** Figure 22-34 shows an uneven arrangement of electrons (e) and protons (p) on a circular arc of radius $r = 2.00$ cm, with angles $\theta_1 = 30.0^\circ$, $\theta_2 = 50.0^\circ$, $\theta_3 = 30.0^\circ$, and $\theta_4 = 20.0^\circ$. What are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the net electric field produced at the center of the arc?

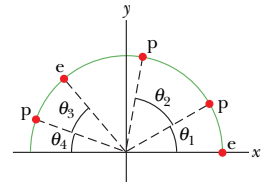


Fig. 22-34 Problem 12.

••13 Figure 22-35 shows a proton (p) on the central axis through a disk with a uniform charge density due to excess electrons. Three of those electrons are shown: electron e_c at the disk center and electrons e_s at opposite sides of the disk, at radius R from the center. The proton is initially at distance $z = R = 2.00$ cm from the disk. At that location, what are the magnitudes of (a) the electric field \vec{E}_c due to electron e_c and (b) the net electric field $\vec{E}_{s,\text{net}}$ due to electrons e_s ? The proton is then moved to $z = R/10.0$. What then are the magnitudes of (c) \vec{E}_c and (d) $\vec{E}_{s,\text{net}}$ at the proton's location? (e) From (a) and (c) we see that as the proton gets nearer to the disk, the magnitude of \vec{E}_c increases. Why does the magnitude of $\vec{E}_{s,\text{net}}$ decrease, as we see from (b) and (d)?

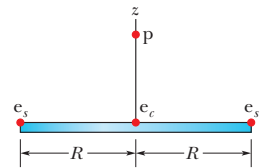


Fig. 22-35 Problem 13.

••14 In Fig. 22-36, particle 1 of charge $q_1 = -5.00q$ and particle 2 of charge $q_2 = +2.00q$ are fixed to an x axis. (a) As a multiple of distance L , at what coordinate on the axis is the net electric field of the particles zero? (b) Sketch the net electric field lines.

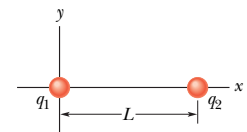


Fig. 22-36 Problem 14.

••15 In Fig. 22-37, the three particles are fixed in place and have charges $q_1 = q_2 = +e$ and $q_3 = +2e$. Distance $a = 6.00$ μm . What are the (a) magnitude and (b) direction of the net electric field at point P due to the particles?

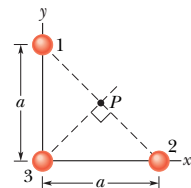


Fig. 22-37 Problem 15.

••16 Figure 22-38 shows a plastic ring of radius $R = 50.0$ cm. Two small charged beads are on the ring: Bead 1 of charge $+2.00$ μC is fixed in place at the left side; bead 2 of charge $+6.00$ μC can be moved along the ring. The two beads produce a net electric field of magni-

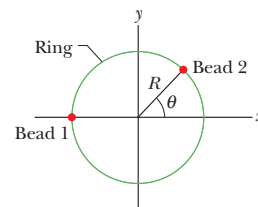


Fig. 22-38 Problem 16.

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ture E at the center of the ring. At what (a) positive and (b) negative value of angle θ should bead 2 be positioned such that $E = 2.00 \times 10^5 \text{ N/C}$?

••17 Two charged beads are on the plastic ring in Fig. 22-39a. Bead 2, which is not shown, is fixed in place on the ring, which has radius $R = 60.0 \text{ cm}$. Bead 1 is initially on the x axis at angle $\theta = 0^\circ$. It is then moved to the opposite side, at angle $\theta = 180^\circ$, through the first and second quadrants of the xy coordinate system. Figure 22-39b gives the x component of the net electric field produced at the origin by the two beads as a function of θ , and Fig. 22-39c gives the y component. The vertical axis scales are set by $E_{xs} = 5.0 \times 10^4 \text{ N/C}$ and $E_{ys} = -9.0 \times 10^4 \text{ N/C}$. (a) At what angle θ is bead 2 located? What are the charges of (b) bead 1 and (c) bead 2?

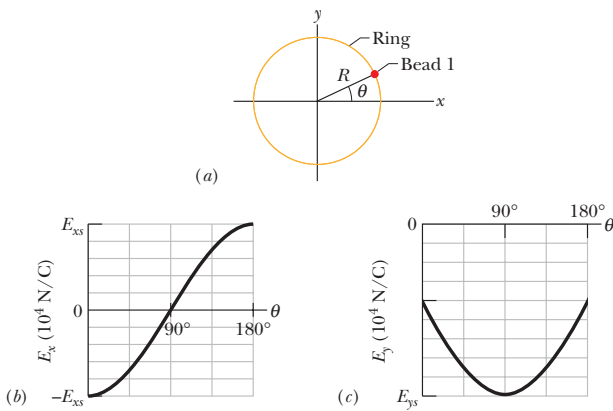


Fig. 22-39 Problem 17.

sec. 22-5 The Electric Field Due to an Electric Dipole

••18 The electric field of an electric dipole along the dipole axis is approximated by Eqs. 22-8 and 22-9. If a binomial expansion is made of Eq. 22-7, what is the next term in the expression for the dipole's electric field along the dipole axis? That is, what is E_{next} in the expression

$$E = \frac{1}{2\pi\epsilon_0} \frac{qd}{z^3} + E_{\text{next}}?$$

••19 Figure 22-40 shows an electric dipole. What are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the dipole's electric field at point P , located at distance $r \gg d$?

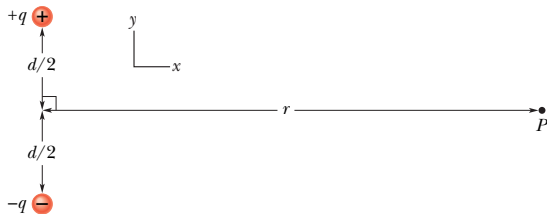


Fig. 22-40 Problem 19.

••20 Equations 22-8 and 22-9 are approximations of the magnitude of the electric field of an electric dipole, at points along the dipole axis. Consider a point P on that axis at distance $z = 5.00d$ from the dipole center (d is the separation distance between the particles of the

dipole). Let E_{appr} be the magnitude of the field at point P as approximated by Eqs. 22-8 and 22-9. Let E_{act} be the actual magnitude. What is the ratio $E_{\text{appr}}/E_{\text{act}}$?

••21 SSM *Electric quadrupole.* Figure 22-41 shows an electric quadrupole. It consists of two dipoles with dipole moments that are equal in magnitude but opposite in direction. Show that the value of E on the axis of the quadrupole for a point P a distance z from its center (assume $z \gg d$) is given by

$$E = \frac{3Q}{4\pi\epsilon_0 z^4},$$

in which $Q (= 2qd^2)$ is known as the *quadrupole moment* of the charge distribution.

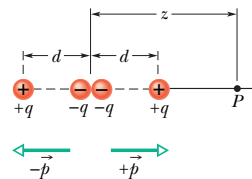


Fig. 22-41 Problem 21.

sec. 22-6 The Electric Field Due to a Line of Charge

•22 *Density, density, density.* (a) A charge $-300e$ is uniformly distributed along a circular arc of radius 4.00 cm , which subtends an angle of 40° . What is the linear charge density along the arc? (b) A charge $-300e$ is uniformly distributed over one face of a circular disk of radius 2.00 cm . What is the surface charge density over that face? (c) A charge $-300e$ is uniformly distributed over the surface of a sphere of radius 2.00 cm . What is the surface charge density over that surface? (d) A charge $-300e$ is uniformly spread through the volume of a sphere of radius 2.00 cm . What is the volume charge density in that sphere?

•23 Figure 22-42 shows two parallel nonconducting rings with their central axes along a common line. Ring 1 has uniform charge q_1 and radius R ; ring 2 has uniform charge q_2 and the same radius R . The rings are separated by distance $d = 3.00R$. The net electric field at point P on the common line, at distance R from ring 1, is zero. What is the ratio q_1/q_2 ?

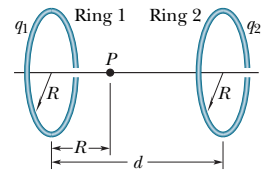


Fig. 22-42 Problem 23.

••24 A thin nonconducting rod with a uniform distribution of positive charge Q is bent into a circle of radius R (Fig. 22-43). The central perpendicular axis through the ring is a z axis, with the origin at the center of the ring. What is the magnitude of the electric field due to the rod at (a) $z = 0$ and (b) $z = \infty$?

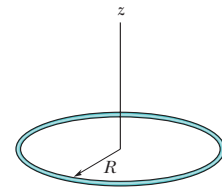


Fig. 22-43 Problem 24.

(c) In terms of R , at what positive value of z is that magnitude maximum? (d) If $R = 2.00 \text{ cm}$ and $Q = 4.00 \mu\text{C}$, what is the maximum magnitude?

••25 Figure 22-44 shows three circular arcs centered on the origin of a coordinate system. On each arc, the uniformly distributed charge is given in terms of $Q = 2.00 \mu\text{C}$. The radii are given in terms of

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$R = 10.0$ cm. What are the (a) magnitude and (b) direction (relative to the positive x direction) of the net electric field at the origin due to the arcs?

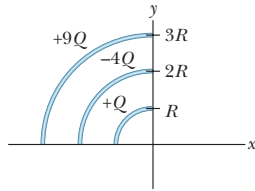


Fig. 22-44 Problem 25.

••26 ILW In Fig. 22-45, a thin glass rod forms a semicircle of radius $r = 5.00$ cm. Charge is uniformly distributed along the rod, with $+q = 4.50$ pC in the upper half and $-q = -4.50$ pC in the lower half. What are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the electric field \vec{E} at P , the center of the semicircle?

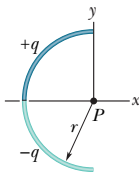


Fig. 22-45 Problem 26.

••27 In Fig. 22-46, two curved plastic rods, one of charge $+q$ and the other of charge $-q$, form a circle of radius $R = 8.50$ cm in an xy plane. The x axis passes through both of the connecting points, and the charge is distributed uniformly on both rods. If $q = 15.0$ pC, what are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the electric field \vec{E} produced at P , the center of the circle?

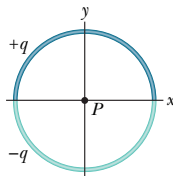


Fig. 22-46 Problem 27.

••28 Charge is uniformly distributed around a ring of radius $R = 2.40$ cm, and the resulting electric field magnitude E is measured along the ring's central axis (perpendicular to the plane of the ring). At what distance from the ring's center is E maximum?

••29 Figure 22-47a shows a nonconducting rod with a uniformly distributed charge $+Q$. The rod forms a half-circle with radius R and produces an electric field of magnitude E_{arc} at its center of curvature P . If the arc is collapsed to a point at distance R from P (Fig. 22-47b), by what factor is the magnitude of the electric field at P multiplied?

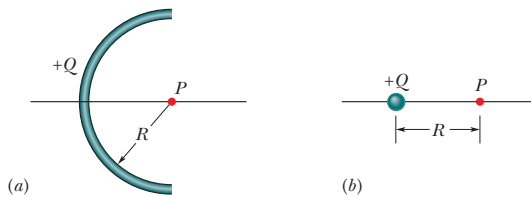


Fig. 22-47 Problem 29.

••30 Figure 22-48 shows two concentric rings, of radii R and $R' = 3.00R$, that lie on the same plane. Point P lies on the central z axis, at distance $D = 2.00R$ from the center of the rings. The smaller ring has uniformly distributed charge $+Q$. In terms of Q , what is the uniformly distributed charge on the larger ring if the net electric field at P is zero?

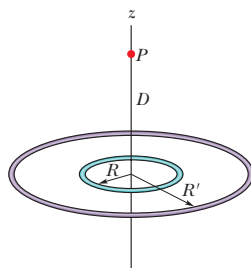


Fig. 22-48 Problem 30.

••31 SSM ILW WWW In Fig. 22-49, a nonconducting rod of length $L = 8.15$ cm has a charge $-q = -4.23$ fC uniformly distributed along its length. (a) What is the linear charge density of the rod? What are the (b) magnitude and (c) direction (relative to the positive direction of the x axis) of the electric field produced at point P , at distance $a = 12.0$ cm from the rod? What is the electric field magnitude produced at distance $a = 50$ m by (d) the rod and (e) a particle of charge $-q = -4.23$ fC that replaces the rod?

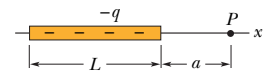


Fig. 22-49 Problem 31.

••32 GO In Fig. 22-50, positive charge $q = 7.81$ pC is spread uniformly along a thin nonconducting rod of length $L = 14.5$ cm. What are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the electric field produced at point P , at distance $R = 6.00$ cm from the rod along its perpendicular bisector?

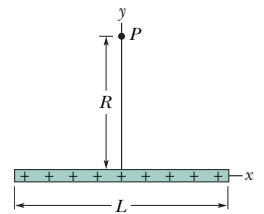


Fig. 22-50 Problem 32.

••33 In Fig. 22-51, a “semi-infinite” nonconducting rod (that is, infinite in one direction only) has uniform linear charge density λ . Show that the electric field \vec{E}_p at point P makes an angle of 45° with the rod and that this result is independent of the distance R . (*Hint*: Separately find the component of \vec{E}_p parallel to the rod and the component perpendicular to the rod.)

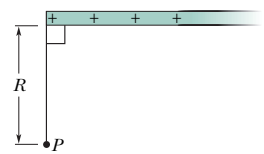


Fig. 22-51 Problem 33.

sec. 22-7 The Electric Field Due to a Charged Disk

•34 A disk of radius 2.5 cm has a surface charge density of $5.3 \mu\text{C}/\text{m}^2$ on its upper face. What is the magnitude of the electric field produced by the disk at a point on its central axis at distance $z = 12$ cm from the disk?

•35 SSM WWW At what distance along the central perpendicular axis of a uniformly charged plastic disk of radius 0.600 m is the magnitude of the electric field equal to one-half the magnitude of the field at the center of the surface of the disk?

••36 A circular plastic disk with radius $R = 2.00$ cm has a uniformly distributed charge $Q = +(2.00 \times 10^6)e$ on one face. A circular ring of width $30 \mu\text{m}$ is centered on that face, with the center of that width at radius $r = 0.50$ cm. In coulombs, what charge is contained within the width of the ring?

••37 Suppose you design an apparatus in which a uniformly charged disk of radius R is to produce an electric field. The field magnitude is most important along the central perpendicular axis of the disk, at a point P at distance $2.00R$ from the disk (Fig. 22-52a). Cost analysis suggests that you switch to a ring of the same outer radius R but with inner radius $R/2.00$ (Fig. 22-52b). Assume that the ring will have the same

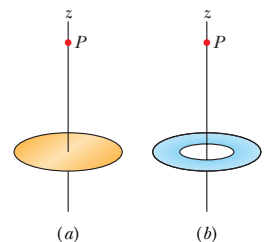


Fig. 22-52 Problem 37.

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surface charge density as the original disk. If you switch to the ring, by what percentage will you decrease the electric field magnitude at P ?

••38 Figure 22-53a shows a circular disk that is uniformly charged. The central z axis is perpendicular to the disk face, with the origin at the disk. Figure 22-53b gives the magnitude of the electric field along that axis in terms of the maximum magnitude E_m at the disk surface. The z axis scale is set by $z_s = 8.0$ cm. What is the radius of the disk?

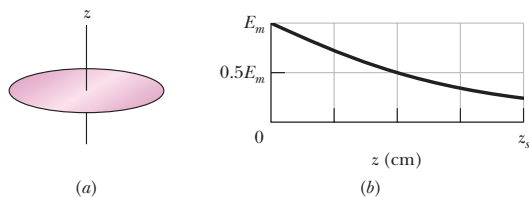


Fig. 22-53 Problem 38.

sec. 22-8 A Point Charge in an Electric Field

•39 In Millikan's experiment, an oil drop of radius $1.64 \mu\text{m}$ and density 0.851 g/cm^3 is suspended in chamber C (Fig. 22-14) when a downward electric field of $1.92 \times 10^5 \text{ N/C}$ is applied. Find the charge on the drop, in terms of e .

•40 **GO** An electron with a speed of $5.00 \times 10^8 \text{ cm/s}$ enters an electric field of magnitude $1.00 \times 10^3 \text{ N/C}$, traveling along a field line in the direction that retards its motion. (a) How far will the electron travel in the field before stopping momentarily, and (b) how much time will have elapsed? (c) If the region containing the electric field is 8.00 mm long (too short for the electron to stop within it), what fraction of the electron's initial kinetic energy will be lost in that region?

•41 **SSM** A charged cloud system produces an electric field in the air near Earth's surface. A particle of charge $-2.0 \times 10^{-9} \text{ C}$ is acted on by a downward electrostatic force of $3.0 \times 10^{-6} \text{ N}$ when placed in this field. (a) What is the magnitude of the electric field? What are the (b) magnitude and (c) direction of the electrostatic force \vec{F}_{el} on the proton placed in this field? (d) What is the magnitude of the gravitational force \vec{F}_g on the proton? (e) What is the ratio F_{el}/F_g in this case?

•42 Humid air breaks down (its molecules become ionized) in an electric field of $3.0 \times 10^6 \text{ N/C}$. In that field, what is the magnitude of the electrostatic force on (a) an electron and (b) an ion with a single electron missing?

•43 **SSM** An electron is released from rest in a uniform electric field of magnitude $2.00 \times 10^4 \text{ N/C}$. Calculate the acceleration of the electron. (Ignore gravitation.)

•44 An alpha particle (the nucleus of a helium atom) has a mass of $6.64 \times 10^{-27} \text{ kg}$ and a charge of $+2e$. What are the (a) magnitude and (b) direction of the electric field that will balance the gravitational force on the particle?

•45 **ILW** An electron on the axis of an electric dipole is 25 nm from the center of the dipole. What is the magnitude of the electrostatic force on the electron if the dipole moment is $3.6 \times 10^{-29} \text{ C}\cdot\text{m}$? Assume that 25 nm is much larger than the dipole charge separation.

•46 An electron is accelerated eastward at $1.80 \times 10^9 \text{ m/s}^2$ by an electric field. Determine the field (a) magnitude and (b) direction.

•47 **SSM** Beams of high-speed protons can be produced in "guns" using electric fields to accelerate the protons. (a) What acceleration would a proton experience if the gun's electric field were $2.00 \times 10^4 \text{ N/C}$? (b) What speed would the proton attain if the field accelerated the proton through a distance of 1.00 cm ?

••48 In Fig. 22-54, an electron (e) is to be released from rest on the central axis of a uniformly charged disk of radius R . The surface charge density on the disk is $+4.00 \mu\text{C/m}^2$. What is the magnitude of the electron's initial acceleration if it is released at a distance (a) R , (b) $R/100$, and (c) $R/1000$ from the center of the disk? (d) Why does the acceleration magnitude increase only slightly as the release point is moved closer to the disk?

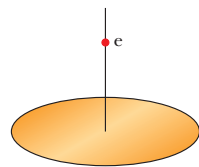


Fig. 22-54 Problem 48.

••49 A 10.0 g block with a charge of $+8.00 \times 10^{-5} \text{ C}$ is placed in an electric field $\vec{E} = (3000\hat{i} - 600\hat{j}) \text{ N/C}$. What are the (a) magnitude and (b) direction (relative to the positive direction of the x axis) of the electrostatic force on the block? If the block is released from rest at the origin at time $t = 0$, what are its (c) x and (d) y coordinates at $t = 3.00 \text{ s}$?

••50 At some instant the velocity components of an electron moving between two charged parallel plates are $v_x = 1.5 \times 10^5 \text{ m/s}$ and $v_y = 3.0 \times 10^3 \text{ m/s}$. Suppose the electric field between the plates is given by $\vec{E} = (120 \text{ N/C})\hat{j}$. In unit-vector notation, what are (a) the electron's acceleration in that field and (b) the electron's velocity when its x coordinate has changed by 2.0 cm ?

••51 **ILW** Assume that a honeybee is a sphere of diameter 1.000 cm with a charge of $+45.0 \text{ pC}$ uniformly spread over its surface. Assume also that a spherical pollen grain of diameter $40.0 \mu\text{m}$ is electrically held on the surface of the sphere because the bee's charge induces a charge of -1.00 pC on the near side of the sphere and a charge of $+1.00 \text{ pC}$ on the far side. (a) What is the magnitude of the net electrostatic force on the grain due to the bee? Next, assume that the bee brings the grain to a distance of 1.000 mm from the tip of a flower's stigma and that the tip is a particle of charge -45.0 pC . (b) What is the magnitude of the net electrostatic force on the grain due to the stigma? (c) Does the grain remain on the bee or does it move to the stigma?

••52 An electron enters a region of uniform electric field with an initial velocity of 40 km/s in the same direction as the electric field, which has magnitude $E = 50 \text{ N/C}$. (a) What is the speed of the electron 1.5 ns after entering this region? (b) How far does the electron travel during the 1.5 ns interval?

••53 **GO** Two large parallel copper plates are 5.0 cm apart and have a uniform electric field between them as depicted in Fig. 22-55. An electron is released from the negative plate at the same time that a proton is released from the positive plate. Neglect the force of the particles on each other and find their distance from the positive plate when they pass each other. (Does it surprise you that you need not know the electric field to solve this problem?)

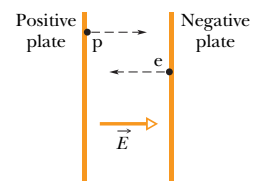


Fig. 22-55 Problem 53.

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••54 GO In Fig. 22-56, an electron is shot at an initial speed of $v_0 = 2.00 \times 10^6$ m/s, at angle $\theta_0 = 40.0^\circ$ from an x axis. It moves through a uniform electric field $\vec{E} = (5.00 \text{ N/C})\hat{j}$. A screen for detecting electrons is positioned parallel to the y axis, at distance $x = 3.00$ m. In unit-vector notation, what is the velocity of the electron when it hits the screen?

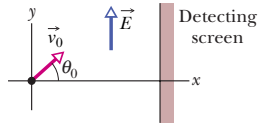


Fig. 22-56 Problem 54.

••55 ILW A uniform electric field exists in a region between two oppositely charged plates. An electron is released from rest at the surface of the negatively charged plate and strikes the surface of the opposite plate, 2.0 cm away, in a time 1.5×10^{-8} s. (a) What is the speed of the electron as it strikes the second plate? (b) What is the magnitude of the electric field \vec{E} ?

sec. 22-9 A Dipole in an Electric Field

•56 An electric dipole consists of charges $+2e$ and $-2e$ separated by 0.78 nm. It is in an electric field of strength 3.4×10^6 N/C. Calculate the magnitude of the torque on the dipole when the dipole moment is (a) parallel to, (b) perpendicular to, and (c) antiparallel to the electric field.

•57 SSM An electric dipole consisting of charges of magnitude 1.50 nC separated by $6.20 \mu\text{m}$ is in an electric field of strength 1100 N/C. What are (a) the magnitude of the electric dipole moment and (b) the difference between the potential energies for dipole orientations parallel and antiparallel to \vec{E} ?

••58 A certain electric dipole is placed in a uniform electric field \vec{E} of magnitude 20 N/C. Figure 22-57 gives the potential energy U of the dipole versus the angle θ between \vec{E} and the dipole moment \vec{p} . The vertical axis scale is set by $U_s = 100 \times 10^{-28}$ J. What is the magnitude of \vec{p} ?

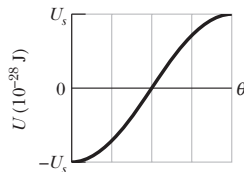


Fig. 22-57 Problem 58.

••59 How much work is required to turn an electric dipole 180° in a uniform electric field of magnitude $E = 46.0$ N/C if $p = 3.02 \times 10^{-25}$ C·m and the initial angle is 64° ?

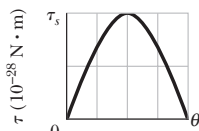


Fig. 22-58 Problem 60.

••60 A certain electric dipole is placed in a uniform electric field \vec{E} of magnitude 40 N/C. Figure 22-58 gives the magnitude τ of the torque on the dipole versus the angle θ between field \vec{E} and the dipole moment \vec{p} . The vertical axis scale is set by $\tau_s = 100 \times 10^{-28}$ N·m. What is the magnitude of \vec{p} ?

••61 Find an expression for the oscillation frequency of an electric dipole of dipole moment \vec{p} and rotational inertia I for small amplitudes of oscillation about its equilibrium position in a uniform electric field of magnitude E .

Additional Problems

62 (a) What is the magnitude of an electron's acceleration in a uniform electric field of magnitude 1.40×10^6 N/C? (b) How long would the electron take, starting from rest, to attain one-tenth the speed of light? (c) How far would it travel in that time?

63 A spherical water drop $1.20 \mu\text{m}$ in diameter is suspended in calm air due to a downward-directed atmospheric electric field of magni-

tude $E = 462$ N/C. (a) What is the magnitude of the gravitational force on the drop? (b) How many excess electrons does it have?

64 Three particles, each with positive charge Q , form an equilateral triangle, with each side of length d . What is the magnitude of the electric field produced by the particles at the midpoint of any side?

65 In Fig. 22-59a, a particle of charge $+Q$ produces an electric field of magnitude E_{part} at point P , at distance R from the particle. In Fig. 22-59b, that same amount of charge is spread uniformly along a circular arc that has radius R and subtends an angle θ . The charge on the arc produces an electric field of magnitude E_{arc} at its center of curvature P . For what value of θ does $E_{\text{arc}} = 0.500E_{\text{part}}$? (*Hint*: You will probably resort to a graphical solution.)

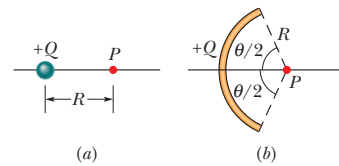


Fig. 22-59 Problem 65.

66 A proton and an electron form two corners of an equilateral triangle of side length 2.0×10^{-6} m. What is the magnitude of the net electric field these two particles produce at the third corner?

67 A charge (uniform linear density $= 9.0$ nC/m) lies on a string that is stretched along an x axis from $x = 0$ to $x = 3.0$ m. Determine the magnitude of the electric field at $x = 4.0$ m on the x axis.

68 In Fig. 22-60, eight particles form a square in which distance $d = 2.0$ cm. The charges are $q_1 = +3e$, $q_2 = +e$, $q_3 = -5e$, $q_4 = -2e$, $q_5 = +3e$, $q_6 = +e$, $q_7 = -5e$, and $q_8 = +e$. In unit-vector notation, what is the net electric field at the square's center?

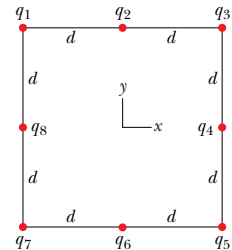


Fig. 22-60 Problem 68.

69 Two particles, each with a charge of magnitude 12 nC, are at two of the vertices of an equilateral triangle with edge length 2.0 m. What is the magnitude of the electric field at the third vertex if (a) both charges are positive and (b) one charge is positive and the other is negative?

70 In one of his experiments, Millikan observed that the following measured charges, among others, appeared at different times on a single drop:

6.563×10^{-19} C	13.13×10^{-19} C	19.71×10^{-19} C
8.204×10^{-19} C	16.48×10^{-19} C	22.89×10^{-19} C
11.50×10^{-19} C	18.08×10^{-19} C	26.13×10^{-19} C

What value for the elementary charge e can be deduced from these data?

71 A charge of 20 nC is uniformly distributed along a straight rod of length 4.0 m that is bent into a circular arc with a radius of 2.0 m. What is the magnitude of the electric field at the center of curvature of the arc?

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72 An electron is constrained to the central axis of the ring of charge of radius R in Fig. 22-10, with $z \ll R$. Show that the electrostatic force on the electron can cause it to oscillate through the ring center with an angular frequency

$$\omega = \sqrt{\frac{eq}{4\pi\epsilon_0 mR^3}},$$

where q is the ring's charge and m is the electron's mass.

73 SSM The electric field in an xy plane produced by a positively charged particle is $7.2(4.0\hat{i} + 3.0\hat{j})$ N/C at the point (3.0, 3.0) cm and $100\hat{i}$ N/C at the point (2.0, 0) cm. What are the (a) x and (b) y coordinates of the particle? (c) What is the charge of the particle?

74 (a) What total (excess) charge q must the disk in Fig. 22-13 have for the electric field on the surface of the disk at its center to have magnitude 3.0×10^6 N/C, the E value at which air breaks down electrically, producing sparks? Take the disk radius as 2.5 cm, and use the listing for air in Table 22-1. (b) Suppose each surface atom has an effective cross-sectional area of 0.015 nm². How many atoms are needed to make up the disk surface? (c) The charge calculated in (a) results from some of the surface atoms having one excess electron. What fraction of these atoms must be so charged?

75 In Fig. 22-61, particle 1 (of charge $+1.00$ μ C), particle 2 (of charge $+1.00$ μ C), and particle 3 (of charge Q) form an equilateral triangle of edge length a . For what value of Q (both sign and magnitude) does the net electric field produced by the particles at the center of the triangle vanish?

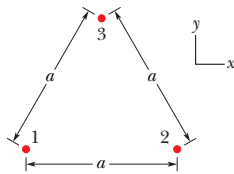


Fig. 22-61 Problems 75 and 86.

76 In Fig. 22-62, an electric dipole swings from an initial orientation i ($\theta_i = 20.0^\circ$) to a final orientation f ($\theta_f = 20.0^\circ$) in a uniform external electric field \vec{E} . The electric dipole moment is 1.60×10^{-27} C·m; the field magnitude is 3.00×10^6 N/C. What is the change in the dipole's potential energy?

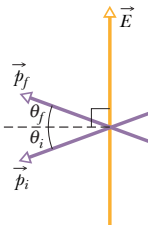


Fig. 22-62 Problem 76.

77 A particle of charge $-q_1$ is at the origin of an x axis. (a) At what location on the axis should a particle of charge $-4q_1$ be placed so that the net electric field is zero at $x = 2.0$ mm on the axis? (b) If, instead, a particle of charge $+4q_1$ is placed at that location, what is the direction (relative to the positive direction of the x axis) of the net electric field at $x = 2.0$ mm?

78 Two particles, each of positive charge q , are fixed in place on a y axis, one at $y = d$ and the other at $y = -d$. (a) Write an expression that gives the magnitude E of the net electric field at points on the x axis given by $x = \alpha d$. (b) Graph E versus α for the range $0 < \alpha < 4$. From the graph, determine the values of α that give (c) the maximum value of E and (d) half the maximum value of E .

79 A clock face has negative point charges $-q, -2q, -3q, \dots, -12q$ fixed at the positions of the corresponding numerals. The clock hands do not perturb the net field due to the point charges. At what time does the hour hand point in the same direction as the electric field vector at the center of the dial? (*Hint:* Use symmetry.)

80 Calculate the electric dipole moment of an electron and a proton 4.30 nm apart.

81 An electric field \vec{E} with an average magnitude of about 150 N/C points downward in the atmosphere near Earth's surface. We wish to "float" a sulfur sphere weighing 4.4 N in this field by charging the sphere. (a) What charge (both sign and magnitude) must be used? (b) Why is the experiment impractical?

82 A circular rod has a radius of curvature $R = 9.00$ cm and a uniformly distributed positive charge $Q = 6.25$ pC and subtends an angle $\theta = 2.40$ rad. What is the magnitude of the electric field that Q produces at the center of curvature?

83 SSM An electric dipole with dipole moment

$$\vec{p} = (3.00\hat{i} + 4.00\hat{j})(1.24 \times 10^{-30} \text{ C}\cdot\text{m})$$

is in an electric field $\vec{E} = (4000 \text{ N/C})\hat{i}$. (a) What is the potential energy of the electric dipole? (b) What is the torque acting on it? (c) If an external agent turns the dipole until its electric dipole moment is

$$\vec{p} = (-4.00\hat{i} + 3.00\hat{j})(1.24 \times 10^{-30} \text{ C}\cdot\text{m}),$$

how much work is done by the agent?

84 In Fig. 22-63, a uniform, upward electric field \vec{E} of magnitude 2.00×10^3 N/C has been set up between two horizontal plates by charging the lower plate positively and the upper plate negatively. The plates have length $L = 10.0$ cm and separation $d = 2.00$ cm. An electron is then shot between the plates from the left edge of the lower plate. The initial velocity \vec{v}_0 of the electron makes an angle $\theta = 45.0^\circ$ with the lower plate and has a magnitude of 6.00×10^6 m/s. (a) Will the electron strike one of the plates? (b) If so, which plate and how far horizontally from the left edge will the electron strike?

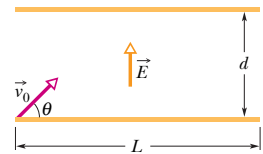


Fig. 22-63 Problem 84.

85 For the data of Problem 70, assume that the charge q on the drop is given by $q = ne$, where n is an integer and e is the elementary charge. (a) Find n for each given value of q . (b) Do a linear regression fit of the values of q versus the values of n and then use that fit to find e .

86 In Fig. 22-61, particle 1 (of charge $+2.00$ pC), particle 2 (of charge -2.00 pC), and particle 3 (of charge $+5.00$ pC) form an equilateral triangle of edge length $a = 9.50$ cm. (a) Relative to the positive direction of the x axis, determine the direction of the force \vec{F}_3 on particle 3 due to the other particles by sketching electric field lines of the other particles. (b) Calculate the magnitude of \vec{F}_3 .

87 In Fig. 22-64, particle 1 of charge $q_1 = 1.00$ pC and particle 2 of charge $q_2 = -2.00$ pC are fixed at a distance $d = 5.00$ cm apart. In unit-vector notation, what is the net electric field at points (a) A , (b) B , and (c) C ? (d) Sketch the electric field lines.

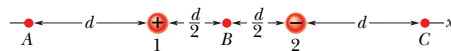


Fig. 22-64 Problem 87.

88 In Fig. 22-8, let both charges be positive. Assuming $z \gg d$, show that E at point P in that figure is then given by

$$E = \frac{1}{4\pi\epsilon_0} \frac{2q}{z^2}.$$

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