BRIDGING PROBLEM CALCULATING ELECTRIC FIELD: HALF A RING OF CHARGE

SOLUTION

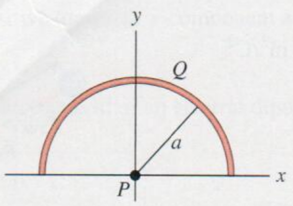
Positive charge Q is uniformly distributed around a semicircle of radius a as shown in **Fig. 21.34**. Find the magnitude and direction of the resulting electric field at point P, the center of curvature of the semicircle.

SOLUTION GUIDE

IDENTIFY and SET UP

1. The target variables are the components of the electric field at P.
2. Divide the semicircle into infinitesimal segments, each of which is a short circular arc of radius a and angle $d\theta$. What is the length of such a segment? How much charge is on a segment?

21.34 Charge uniformly distributed around a semicircle.



3. Consider an infinitesimal segment located at an angular position θ on the semicircle, measured from the lower right corner of the semicircle at $x = a$, $y = 0$. (Thus $\theta = \pi/2$ at $x = 0$, $y = a$ and $\theta = \pi$ at $x = -a$, $y = 0$.) What are the x- and y-components of the electric field at P (dE_x and dE_y) produced by just this segment?

EXECUTE

4. Integrate your expressions for dE_x and dE_y from $\theta = 0$ to $\theta = \pi$. The results will be the x-component and y-component of the electric field at P.
5. Use your results from step 4 to find the magnitude and direction of the field at P.

EVALUATE

6. Does your result for the electric-field magnitude have the correct units?
7. Explain how you could have found the x-component of the electric field by using a symmetry argument.
8. What would be the electric field at P if the semicircle were extended to a full circle centered at P?

Problems

For assigned homework and other learning materials, go to MasteringPhysics®. MP

•, ••, •••: Difficulty levels. **CP**: Cumulative problems incorporating material from earlier chapters. **CALC**: Problems requiring calculus. **DATA**: Problems involving real data, scientific evidence, experimental design, and/or statistical reasoning. **BIO**: Biosciences problems.

DISCUSSION QUESTIONS

Q21.1 If you peel two strips of transparent tape off the same roll and immediately let them hang near each other, they will repel each other. If you then stick the sticky side of one to the shiny side of the other and rip them apart, they will attract each other. Give a plausible explanation, involving transfer of electrons between the strips of tape, for this sequence of events.

Q21.2 Two metal spheres are hanging from nylon threads. When you bring the spheres close to each other, they tend to attract. Based on this information alone, discuss all the possible ways that the spheres could be charged. Is it possible that after the spheres touch, they will cling together? Explain.

Q21.3 The electric force between two charged particles becomes weaker with increasing distance. Suppose instead that the electric force were *independent* of distance. In this case, would a charged comb still cause a neutral insulator to become polarized as in Fig. 21.8? Why or why not? Would the neutral insulator still be attracted to the comb? Again, why or why not?

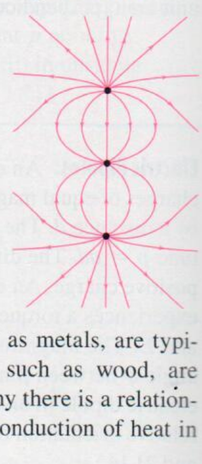
Q21.4 Your clothing tends to cling together after going through the dryer. Why? Would you expect more or less clinging if all your clothing were made of the same material (say, cotton) than if you dried different kinds of clothing together? Again, why? (You may want to experiment with your next load of laundry.)

Q21.5 An uncharged metal sphere hangs from a nylon thread. When a positively charged glass rod is brought close to the metal sphere, the sphere is drawn toward the rod. But if the sphere touches the rod, it suddenly flies away from the rod. Explain why the sphere is first attracted and then repelled.

Q21.6 BIO Estimate how many electrons there are in your body. Make any assumptions you feel are necessary, but clearly state what they are. (*Hint:* Most of the atoms in your body have equal numbers of electrons, protons, and neutrons.) What is the combined charge of all these electrons?

Q21.7 Figure Q21.7 shows some of the electric field lines due to three point charges arranged along the vertical axis. All three charges have the same magnitude. (a) What are the signs of the three charges? Explain your reasoning. (b) At what point(s) is the magnitude of the electric field the smallest? Explain your reasoning. Explain how the fields produced by each individual point charge combine to give a small net field at this point or points.

Figure **Q21.7**



Q21.8 Good conductors of electricity, such as metals, are typically good conductors of heat; insulators, such as wood, are typically poor conductors of heat. Explain why there is a relationship between conduction of electricity and conduction of heat in these materials.

Q21.9 Suppose that the charge shown in Fig. 21.28a is fixed in position. A small, positively charged particle is then placed at some location and released. Will the trajectory of the particle follow an electric field line? Why or why not? Suppose instead that the particle is placed at some point in Fig. 21.28b and released (the positive and negative charges shown are fixed in position). Will its trajectory follow an electric field line? Again, why or why not? Explain any differences between your answers for the two situations.

Q21.10 Two identical metal objects are mounted on insulating stands. Describe how you could place charges of opposite sign but exactly equal magnitude on the two objects.

Q21.11 Because the charges on the electron and proton have the same absolute value, atoms are electrically neutral. Suppose that this is not precisely true, and the absolute value of the charge of the electron is less than the charge of the proton by 0.00100%. Estimate what the net charge of this textbook would be under these circumstances. Make any assumptions you feel are justified, but state clearly what they are. (*Hint:* Most of the atoms in this textbook have equal numbers of electrons, protons, and neutrons.) What would be the magnitude of the electric force between two textbooks placed 5.0 m apart? Would this force be attractive or repulsive? Discuss how the fact that ordinary matter is stable shows that the absolute values of the charges on the electron and proton must be identical to a *very* high level of accuracy.

Q21.12 If you walk across a nylon rug and then touch a large metal object such as a doorknob, you may get a spark and a shock. Why does this tend to happen more on dry days than on humid days? (*Hint:* See Fig. 21.30.) Why are you less likely to get a shock if you touch a *small* metal object, such as a paper clip?

Q21.13 What is the difference between net charge and free charge? Does the wiring of your house contain free charge?

Q21.14 When two point charges of equal mass and charge are released on a frictionless table, each has an initial acceleration (magnitude) a_0. If instead you keep one fixed and release the other one, what will be its initial acceleration: a_0, $2a_0$, or $a_0/2$? Explain.

Q21.15 A point charge of mass m and charge Q and another point charge of mass m but charge $2Q$ are released on a frictionless table. If the charge Q has an initial acceleration a_0, what will be the acceleration of $2Q$: a_0, $2a_0$, $4a_0$, $a_0/2$, or $a_0/4$? Explain.

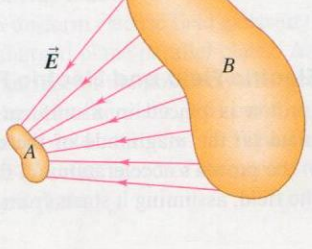
Q21.16 A proton is placed in a uniform electric field and then released. Then an electron is placed at this same point and released. Do these two particles experience the same force? The same acceleration? Do they move in the same direction when released?

Q21.17 In Example 21.1 (Section 21.3) we saw that the electric force between two α particles is of the order of 10^{35} times as strong as the gravitational force. So why do we readily feel the gravity of the earth but no electric force from it?

Q21.18 Do you get +6 V and −6 V from the two terminals in a 12 V car battery?

Q21.19 Two irregular objects A and B carry charges of opposite sign. **Figure Q21.19** shows the electric field lines near each of these objects. (a) Which object is positive, A or B? How do you know? (b) Where is the electric field stronger, close to A or close to B? How do you know?

Figure **Q21.19**

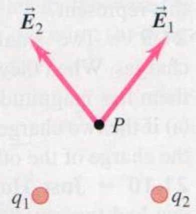


Q21.20 How does electrostatic discharge to neutralize huge charge neutrality manifest in nature?

Q21.21 How is damage from the situation in the previous question prevented?

Q21.22 The electric fields at point P due to the positive charges q_1 and q_2 are shown in **Fig. Q21.22**. Does the fact that they cross each other violate the statement in Section 21.6 that electric field lines never cross? Explain.

Figure **Q21.22**



Q21.23 Precision electrical equipment measure very minute changes in current or electrical field and are usually sensitively calibrated. In such equipment, the circuits are usually housed in boxes lined with fine wire mesh. Why?

EXERCISES

Section 21.3 Coulomb's Law

21.1 •• Excess electrons are placed on a small lead sphere with mass 7.90 g so that its net charge is -3.10×10^{-9} C. (a) Find the number of excess electrons on the sphere. (b) How many excess electrons are there per lead atom? The atomic number of lead is 82, and its atomic mass is 207 g/mol.

21.2 • Lightning occurs when there is a flow of electric charge (principally electrons) between the ground and a thundercloud. The maximum rate of charge flow in a lightning bolt is about 20,000 C/s; this lasts for 100 μs or less. How much charge flows between the ground and the cloud in this time? How many electrons flow during this time?

21.3 •• If a proton and an electron are released when they are 2.0×10^{-10} m apart (a typical atomic distance), find the initial acceleration of each particle.

21.4 • **Particles in a Gold Ring.** You have a pure (24-karat) gold ring of mass 10.8 g. Gold has an atomic mass of 197 g/mol and an atomic number of 79. (a) How many protons are in the ring, and what is their total positive charge? (b) If the ring carries no net charge, how many electrons are in it?

21.5 • BIO **Signal Propagation in Neurons.** *Neurons* are components of the nervous system of the body that transmit signals as electric impulses travel along their length. These impulses propagate when charge suddenly rushes into and then out of a part of the neuron called an *axon*. Measurements have shown that, during the inflow part of this cycle, approximately 5.6×10^{11} Na^+ (sodium ions) per meter, each with charge $+e$, enter the axon. How many coulombs of charge enter a 1.3-cm length of the axon during this process?

21.6 • Two small spheres spaced 20.0 cm apart have equal charge. How many excess electrons must be present on each sphere if the magnitude of the force of repulsion between them is 3.33×10^{-21} N?

21.7 •• An average human weighs about 600 N. If each of two average humans could carry 2.5 C of excess charge, one positive and one negative, how far apart would they have to be for the electric attraction between them to equal their 600-N weight?

21.8 •• Two small aluminum spheres, each having mass 0.0250 kg, are separated by 80.0 cm. (a) How many electrons does each sphere contain? (The atomic mass of aluminum is 26.982 g/mol, and its atomic number is 13.) (b) How many electrons would have to be removed from one sphere and added to the other to cause an attractive force between the spheres of magnitude 1.00×10^4 N (roughly 1 ton)? Assume that the spheres may be treated as point charges. (c) What fraction of all the electrons in each sphere does this represent?

21.9 •• Two small plastic spheres are given positive electric charges. When they are 15.4 cm apart, the repulsive force between them has magnitude 0.205 N. What is the charge on each sphere (a) if the two charges are equal and (b) if one sphere has four times the charge of the other?

21.10 •• **Just How Strong Is the Electric Force?** Suppose you had two small boxes, each containing 1.0 g of protons. (a) If one were placed on the moon by an astronaut and the other were left on the earth, and if they were connected by a very light (and very long!) string, what would be the tension in the string? Express your answer in newtons and in pounds. Do you need to take into account the gravitational forces of the earth and moon on the protons? Why? (b) What gravitational force would each box of protons exert on the other box?

21.11 • In an experiment in space, one proton is held fixed and another proton is released from rest a distance of 3.50 mm away. (a) What is the initial acceleration of the proton after it is released? (b) Sketch qualitative (no numbers!) acceleration–time and velocity–time graphs of the released proton's motion.

21.12 • A negative charge of $-0.550\ \mu$C exerts an upward 0.600-N force on an unknown charge that is located 0.300 m directly below the first charge. What are (a) the value of the unknown charge (magnitude and sign); (b) the magnitude and direction of the force that the unknown charge exerts on the -0.550-μC charge?

21.13 •• Three point charges are arranged on a line. Charge $q_3 = +5.00$ nC and is at the origin. Charge $q_2 = -2.00$ nC and is at $x = +3.50$ cm. Charge q_1 is at $x = +2.00$ cm. What is q_1 (magnitude and sign) if the net force on q_3 is zero?

21.14 •• In Example 21.4, suppose the point charge on the y-axis at $y = -0.30$ m has negative charge $-2.0\ \mu$C, and the other charges remain the same. Find the magnitude and direction of the net force on Q. How does your answer differ from that in Example 21.4? Explain the differences.

21.15 •• In Example 21.3, calculate the net force on charge q_1.

21.16 •• In Example 21.4, what is the net force (magnitude and direction) on charge q_1 exerted by the other two charges?

21.17 •• Three point charges are arranged along the x-axis. Charge $q_1 = +3.00\ \mu$C is at the origin, and charge $q_2 = -5.00\ \mu$C is at $x = 0.200$ m. Charge $q_3 = -8.00\ \mu$C. Where is q_3 located if the net force on q_1 is 7.00 N in the $-x$-direction?

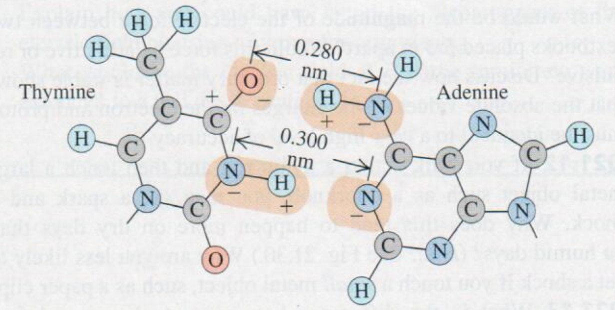
21.18 •• Repeat Exercise 21.17 for $q_3 = +8.00\ \mu$C.

21.19 •• Two point charges are located on the y-axis as follows: charge $q_1 = -1.80$ nC at $y = -0.575$ m, and charge $q_2 = +3.20$ nC at the origin ($y = 0$). What is the total force (magnitude and direction) exerted by these two charges on a third charge $q_3 = +5.35$ nC located at $y = -0.420$ m?

21.20 •• Two point charges are placed on the x-axis as follows: Charge $q_1 = +3.96$ nC is located at $x = 0.199$ m, and charge $q_2 = +5.02$ nC is at $x = -0.298$ m. What are the magnitude and direction of the total force exerted by these two charges on a negative point charge $q_3 = -6.01$ nC that is placed at the origin?

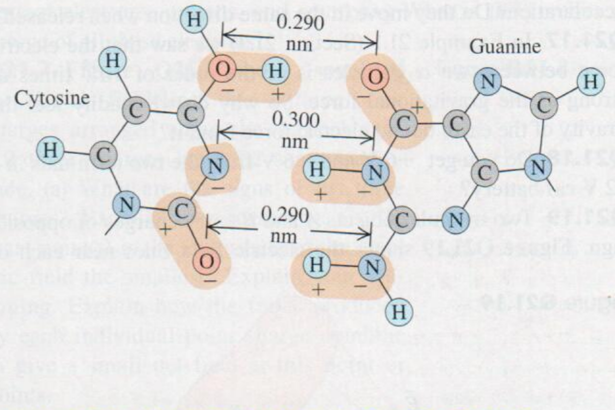
21.21 •• BIO **Base Pairing in DNA, I.** The two sides of the DNA double helix are connected by pairs of bases (adenine, thymine, cytosine, and guanine). Because of the geometric shape of these molecules, adenine bonds with thymine and cytosine bonds with guanine. **Figure E21.21** shows the bonding of thymine and adenine. Each charge shown is $\pm e$, and the H—N distance is 0.110 nm. (a) Calculate the *net* force that thymine exerts on adenine. Is it attractive or repulsive? To keep the calculations fairly simple, yet reasonable, consider only the forces due to the O—H—N and the N—H—N combinations, assuming that these two combinations are parallel to each other. Remember, however, that in the O—H—N set, the O^- exerts a force on both the H^+ and the N^-, and likewise along the N—H—N set. (b) Calculate the force on the electron in the hydrogen atom, which is 0.0529 nm from the proton. Then compare the strength of the bonding force of the electron in hydrogen with the bonding force of the adenine–thymine molecules.

Figure **E21.21**



21.22 •• BIO **Base Pairing in DNA, II.** Refer to Exercise 21.21. **Figure E21.22** shows the bonding of cytosine and guanine. The O—H and H—N distances are each 0.110 nm. In this case, assume that the bonding is due only to the forces along the O—H—O, N—H—N, and O—H—N combinations, and assume also that these three combinations are parallel to each other. Calculate the *net* force that cytosine exerts on guanine due to the preceding three combinations. Is this force attractive or repulsive?

Figure **E21.22**



Section 21.4 Electric Field and Electric Forces

21.23 • CP A proton is placed in a uniform electric field of 2950 N/C. Calculate (a) the magnitude of the electric force felt by the proton; (b) the proton's acceleration; (c) the proton's speed after 1.80 μs in the field, assuming it starts from rest.

21.24 • A particle has charge −3.35 nC. (a) Find the magnitude and direction of the electric field due to this particle at a point 0.200 m directly above it. (b) At what distance from this particle does its electric field have a magnitude of 11.2 N/C?

21.25 • **CP** A proton is traveling horizontally to the right at 4.50×10^6 m/s. (a) Find the magnitude and direction of the weakest electric field that can bring the proton uniformly to rest over a distance of 3.30 cm. (b) How much time does it take the proton to stop after entering the field? (c) What minimum field (magnitude and direction) would be needed to stop an electron under the conditions of part (a)?

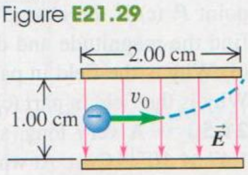
21.26 • **CP** An electron is released from rest in a uniform electric field. The electron accelerates vertically upward, traveling 4.50 m in the first 3.00 μs after it is released. (a) What are the magnitude and direction of the electric field? (b) Are we justified in ignoring the effects of gravity? Justify your answer quantitatively.

21.27 •• (a) What must the charge (sign and magnitude) of a 1.46-g particle be for it to remain stationary when placed in a downward-directed electric field of magnitude 680 N/C? (b) What is the magnitude of an electric field in which the electric force on a proton is equal in magnitude to its weight?

21.28 •• **Electric Field of the Earth.** The earth has a net electric charge that causes a field at points near its surface equal to 150 N/C and directed in toward the center of the earth. (a) What magnitude and sign of charge would a 56-kg human have to acquire to overcome his or her weight by the force exerted by the earth's electric field? (b) What would be the force of repulsion between two people each with the charge calculated in part (a) and separated by a distance of 100 m? Is use of the earth's electric field a feasible means of flight? Why or why not?

21.29 •• **CP** An electron is projected with an initial speed $v_0 = 2.00 \times 10^6$ m/s into the uniform field between two parallel plates (**Fig. E21.29**). Assume that the field between the plates is uniform and directed vertically downward and that the field outside the plates is zero. The electron enters the field at a point midway between the plates. (a) If the electron just misses the upper plate as it emerges from the field, find the magnitude of the electric field. (b) Suppose that the electron in Fig. E21.29 is replaced by a proton with the same initial speed v_0. Would the proton hit one of the plates? If not, what would be the magnitude and direction of its vertical displacement as it exits the region between the plates? (c) Compare the paths traveled by the electron and the proton, and explain the differences. (d) Discuss whether it is reasonable to ignore the effects of gravity for each particle.

Figure **E21.29**



21.30 • (a) Calculate the magnitude and direction (relative to the +x-axis) of the electric field in Example 21.6. (b) A −2.5-nC point charge is placed at point *P* in Fig. 21.19. Find the magnitude and direction of (i) the force that the −8.0-nC charge at the origin exerts on this charge and (ii) the force that this charge exerts on the −8.0-nC charge at the origin.

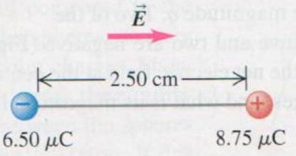
21.31 •• **CP** In Exercise 21.29, what is the speed of the electron as it emerges from the field?

21.32 •• **CP** A uniform electric field exists in the region between two oppositely charged plane parallel plates. A proton is released from rest at the surface of the positively charged plate and strikes the surface of the opposite plate, 1.61 cm distant from the first, in a time interval of 1.44×10^{-6} s. (a) Find the magnitude of the electric field. (b) Find the speed of the proton when it strikes the negatively charged plate.

21.33 • A point charge is at the origin. With this point charge as the source point, what is the unit vector $\hat{r}$ in the direction of the field point (a) at $x = 0$, $y = -1.35$ m; (b) at $x = 12.0$ cm, $y = 12.0$ cm; (c) at $x = -1.10$ m, $y = 2.60$ m? Express your results in terms of the unit vectors $\hat{\imath}$ and $\hat{\jmath}$.

21.34 •• A +8.75-μC point charge is glued down on a horizontal frictionless table. It is tied to a −6.50-μC point charge by a light, nonconducting 2.50-cm wire. A uniform electric field of magnitude 1.85×10^8 N/C is directed parallel to the wire, as shown in **Fig. E21.34**. (a) Find the tension in the wire. (b) What would the tension be if both charges were negative?

Figure **E21.34**

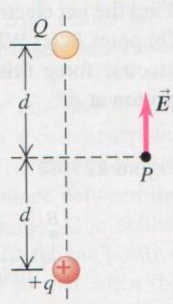


21.35 •• (a) An electron is moving east in a uniform electric field of 1.53 N/C directed to the west. At point *A*, the velocity of the electron is 4.45×10^5 m/s toward the east. What is the speed of the electron when it reaches point *B*, 0.360 m east of point *A*? (b) A proton is moving in the uniform electric field of part (a). At point *A*, the velocity of the proton is 1.89×10^4 m/s, east. What is the speed of the proton at point *B*?

Section 21.5 Electric-Field Calculations

21.36 • Two point charges *Q* and $+q$ (where *q* is positive) produce the net electric field shown at point *P* in **Fig. E21.36**. The field points parallel to the line connecting the two charges. (a) What can you conclude about the sign and magnitude of *Q*? Explain your reasoning. (b) If the lower charge were negative instead, would it be possible for the field to have the direction shown in the figure? Explain your reasoning.

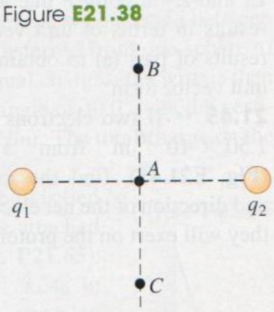
Figure **E21.36**



21.37 •• Two positive point charges *q* are placed on the *x*-axis, one at $x = a$ and one at $x = -a$. (a) Find the magnitude and direction of the electric field at $x = 0$. (b) Derive an expression for the electric field at points on the *x*-axis. Use your result to graph the *x*-component of the electric field as a function of *x*, for values of *x* between $-4a$ and $+4a$.

21.38 • The two charges q_1 and q_2 shown in **Fig. E21.38** have equal magnitudes. What is the direction of the net electric field due to these two charges at points *A* (midway between the charges), *B*, and *C* if (a) both charges are negative, (b) both charges are positive, (c) q_1 is positive and q_2 is negative.

Figure **E21.38**

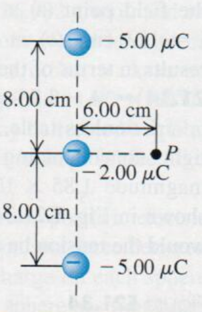


21.39 • A +2.00-nC point charge is at the origin, and a second −5.00-nC point charge is on the *x*-axis at $x = 0.800$ m. (a) Find the electric field (magnitude and direction) at each of the following points on the *x*-axis: (i) $x = 0.200$ m; (ii) $x = 1.20$ m; (iii) $x = -0.200$ m. (b) Find the net electric force that the two charges would exert on an electron placed at each point in part (a).

21.40 • Repeat Exercise 21.39, but now let the charge at the origin be −4.00 nC.

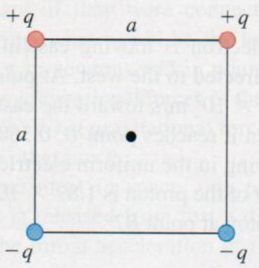
21.41 • Three negative point charges lie along a line as shown in **Fig. E21.41**. Find the magnitude and direction of the electric field this combination of charges produces at point P, which lies 6.00 cm from the −2.00-μC charge measured perpendicular to the line connecting the three charges.

Figure **E21.41**



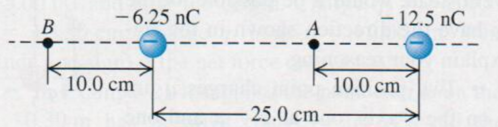
21.42 •• A point charge is placed at each corner of a square with side length a. All charges have magnitude q. Two of the charges are positive and two are negative (**Fig. E21.42**). What is the direction of the net electric field at the center of the square due to the four charges, and what is its magnitude in terms of q and a?

Figure **E21.42**



21.43 • Two point charges are separated by 25.0 cm (**Fig. E21.43**). Find the net electric field these charges produce at (a) point A and (b) point B. (c) What would be the magnitude and direction of the electric force this combination of charges would produce on a proton at A?

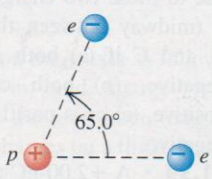
Figure **E21.43**



21.44 •• Point charge $q_1 = -5.00$ nC is at the origin and point charge $q_2 = +3.00$ nC is on the x-axis at $x = 3.00$ cm. Point P is on the y-axis at $y = 4.00$ cm. (a) Calculate the electric fields $\vec{E}_1$ and $\vec{E}_2$ at point P due to the charges q_1 and q_2. Express your results in terms of unit vectors (see Example 21.6). (b) Use the results of part (a) to obtain the resultant field at P, expressed in unit vector form.

21.45 •• If two electrons are each 1.50×10^{-10} m from a proton (**Fig. E21.45**), find the magnitude and direction of the net electric force they will exert on the proton.

Figure **E21.45**



21.46 •• **BIO Electric Field of Axons.** A nerve signal is transmitted through a neuron when an excess of Na^+ ions suddenly enters the axon, a long cylindrical part of the neuron. Axons are approximately 10.0 μm in diameter, and measurements show that about 5.6×10^{11} Na^+ ions per meter (each of charge $+e$) enter during this process. Although the axon is a long cylinder, the charge does not all enter everywhere at the same time. A plausible model would be a series of point charges moving along the axon. Consider a 0.10-mm length of the axon and model it as a point charge. (a) If the charge that enters each meter of the axon gets distributed uniformly along it, how many coulombs of charge enter a 0.10-mm length of the axon? (b) What electric field (magnitude and direction) does the sudden influx of charge produce at the surface of the body if the axon is 5.00 cm below the skin? (c) Certain sharks can respond to electric fields as weak as 1.0 μN/C. How far from this segment of axon could a shark be and still detect its electric field?

21.47 • In a rectangular coordinate system a positive point charge $q = 6.00 \times 10^{-9}$ C is placed at the point $x = +0.150$ m, $y = 0$, and an identical point charge is placed at $x = -0.150$ m, $y = 0$. Find the x- and y-components, the magnitude, and the direction of the electric field at the following points: (a) the origin; (b) $x = 0.300$ m, $y = 0$; (c) $x = 0.150$ m, $y = -0.400$ m; (d) $x = 0$, $y = 0.200$ m.

21.48 •• A point charge $q_1 = -4.00$ nC is at the point $x = 0.600$ m, $y = 0.800$ m, and a second point charge $q_2 = +6.00$ nC is at the point $x = 0.600$ m, $y = 0$. Calculate the magnitude and direction of the net electric field at the origin due to these two point charges.

21.49 •• A charge of −8.00 nC is spread uniformly over the surface of one face of a nonconducting disk of radius 1.05 cm. (a) Find the magnitude and direction of the electric field this disk produces at a point P on the axis of the disk a distance of 2.50 cm from its center. (b) Suppose that the charge were all pushed away from the center and distributed uniformly on the outer rim of the disk. Find the magnitude and direction of the electric field at point P. (c) If the charge is all brought to the center of the disk, find the magnitude and direction of the electric field at point P. (d) Why is the field in part (a) stronger than the field in part (b)? Why is the field in part (c) the strongest of the three fields?

21.50 •• A very long, straight wire has charge per unit length 1.47×10^{-10} C/m. At what distance from the wire is the electric-field magnitude equal to 2.52 N/C?

21.51 • A ring-shaped conductor with radius $a = 2.10$ cm has a total positive charge $Q = +0.129$ nC uniformly distributed around it (see Fig. 21.23). The center of the ring is at the origin of coordinates O. (a) What is the electric field (magnitude and direction) at point P, which is on the x-axis at $x = 41.0$ cm? (b) A point charge $q = -3.00$ μC is placed at P. What are the magnitude and direction of the force exerted *by* the charge q *on* the ring?

21.52 •• A straight, nonconducting plastic wire 9.00 cm long carries a charge density of +125 nC/m distributed uniformly along its length. It is lying on a horizontal tabletop. (a) Find the magnitude and direction of the electric field this wire produces at a point 4.50 cm directly above its midpoint. (b) If the wire is now bent into a circle lying flat on the table, find the magnitude and direction of the electric field it produces at a point 4.50 cm directly above its center.

Section 21.7 Electric Dipoles

21.53 • Point charges $q_1 = -4.2$ nC and $q_2 = +4.2$ nC are separated by 3.5 mm, forming an electric dipole. (a) Find the electric dipole moment (magnitude and direction). (b) The charges are in a uniform electric field whose direction makes an angle of 36.8° with the line connecting the charges. What is the magnitude of this field if the torque exerted on the dipole has magnitude 7.50×10^{-9} N·m?

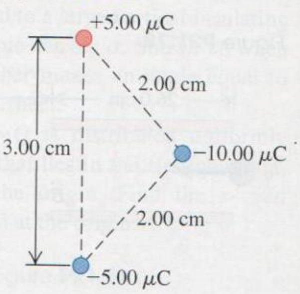
21.54 • The ammonia molecule (NH_3) has a dipole moment of 5.0×10^{-30} C · m. Ammonia molecules in the gas phase are placed in a uniform electric field $\vec{E}$ with magnitude 1.8×10^6 N/C. (a) What is the change in electric potential energy when the dipole moment of a molecule changes its orientation with respect to $\vec{E}$ from parallel to perpendicular? (b) At what absolute temperature T is the average translational kinetic energy $\frac{3}{2}kT$ of a molecule equal to the change in potential energy calculated in part (a)? (*Note:* Above this temperature, thermal agitation prevents the dipoles from aligning with the electric field.)

21.55 • **Torque on a Dipole.** An electric dipole with dipole moment $\vec{p}$ is in a uniform external electric field $\vec{E}$. (a) Find the orientations of the dipole for which the torque on the dipole is zero. (b) Which of the orientations in part (a) is stable, and which is unstable? (*Hint:* Consider a small rotation away from the equilibrium position and see what happens.) (c) Show that for the stable orientation in part (b), the dipole's own electric field tends to oppose the external field.

21.56 • The dipole moment of the water molecule (H_2O) is 6.17×10^{-30} C · m. Consider a water molecule located at the origin whose dipole moment $\vec{p}$ points in the $+x$-direction. A chlorine ion (Cl^-), of charge -1.60×10^{-19} C, is located at $x = 3.00 \times 10^{-9}$ m. Find the magnitude and direction of the electric force that the water molecule exerts on the chlorine ion. Is this force attractive or repulsive? Assume that x is much larger than the separation d between the charges in the dipole, so that the approximate expression for the electric field along the dipole axis derived in Example 21.14 can be used.

21.57 • Three charges are at the corners of an isosceles triangle as shown in **Fig. E21.57.** The ± 5.00-μC charges form a dipole. (a) Find the force (magnitude and direction) the -10.00-μC charge exerts on the dipole. (b) For an axis perpendicular to the line connecting the ± 5.00-μC charges at the midpoint of this line, find the torque (magnitude and direction) exerted on the dipole by the -10.00-μC charge.

Figure **E21.57**



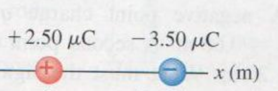
21.58 •• Consider the electric dipole of Example 21.14. (a) Derive an expression for the magnitude of the electric field produced by the dipole at a point on the x-axis in Fig. 21.33. What is the direction of this electric field? (b) How does the electric field at points on the x-axis depend on x when x is very large?

PROBLEMS

21.59 ••• Four identical charges Q are placed at the corners of a square of side L. (a) In a free-body diagram, show all of the forces that act on one of the charges. (b) Find the magnitude and direction of the total force exerted on one charge by the other three charges.

21.60 ••• Two charges are placed on the x-axis: one, of 2.50 μC, at the origin and the other, of -3.50 μC, at $x = 0.600$ m (**Fig. P21.60**). Find the position on the x-axis where the net force on a small charge $+q$ would be zero.

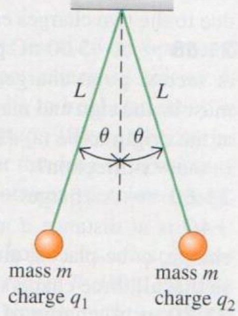
Figure **P21.60**



21.61 •• A charge $q_1 = +5.00$ nC is placed at the origin of an xy-coordinate system, and a charge $q_2 = -2.00$ nC is placed on the positive x-axis at $x = 4.00$ cm. (a) If a third charge $q_3 = +6.00$ nC is now placed at the point $x = 4.00$ cm, $y = 3.00$ cm, find the x- and y-components of the total force exerted on this charge by the other two. (b) Find the magnitude and direction of this force.

21.62 •• **CP** Two identical spheres with mass m are hung from silk threads of length L (**Fig. P21.62**). The spheres have the same charge, so $q_1 = q_2 = q$. The radius of each sphere is very small compared to the distance between the spheres, so they may be treated as point charges. Show that if the angle θ is small, the equilibrium separation d between the spheres is $d = (q^2L/2\pi\epsilon_0 mg)^{1/3}$. (*Hint:* If θ is small, then $\tan\theta \cong \sin\theta$.)

Figure **P21.62**

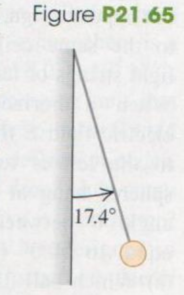


21.63 ••• **CP** Two small spheres with mass $m = 14.3$ g are hung by silk threads of length $L = 1.25$ m from a common point (Fig. P21.62). When the spheres are given equal quantities of negative charge, so that $q_1 = q_2 = q$, each thread hangs at $\theta = 30.0°$ from the vertical. (a) Draw a diagram showing the forces on each sphere. Treat the spheres as point charges. (b) Find the magnitude of q. (c) Both threads are now shortened to length $L = 0.600$ m, while the charges q_1 and q_2 remain unchanged. What new angle will each thread make with the vertical? (*Hint:* This part of the problem can be solved numerically by using trial values for θ and adjusting the values of θ until a self-consistent answer is obtained.)

21.64 •• **CP** Two identical spheres are each attached to silk threads of length $L = 0.500$ m and hung from a common point (Fig. P21.62). Each sphere has mass $m = 8.00$ g. The radius of each sphere is very small compared to the distance between the spheres, so they may be treated as point charges. One sphere is given positive charge q_1, and the other a different positive charge q_2; this causes the spheres to separate so that when the spheres are in equilibrium, each thread makes an angle $\theta = 20.0°$ with the vertical. (a) Draw a free-body diagram for each sphere when in equilibrium, and label all the forces that act on each sphere. (b) Determine the magnitude of the electrostatic force that acts on each sphere, and determine the tension in each thread. (c) Based on the given information, what can you say about the magnitudes of q_1 and q_2? Explain. (d) A small wire is now connected between the spheres, allowing charge to be transferred from one sphere to the other until the two spheres have equal charges; the wire is then removed. Each thread now makes an angle of 30.0° with the vertical. Determine the original charges. (*Hint:* The total charge on the pair of spheres is conserved.)

21.65 •• **CP** A small 13.0-g plastic ball is tied to a very light 27.2-cm string that is attached to the vertical wall of a room (**Fig. P21.65**). A uniform horizontal electric field exists in this room. When the ball has been given an excess charge of -1.10 μC, you observe that it remains suspended, with the string making an angle of 17.4° with the wall. Find the magnitude and direction of the electric field in the room.

Figure **P21.65**



21.66 •• Point charge $q_1 = -6.00 \times 10^{-6}$ C is on the x-axis at $x = -0.200$ m. Point charge q_2 is on the x-axis at $x = +0.400$ m. Point charge $q_3 = +3.00 \times 10^{-6}$ C is at the origin. What is q_2 (magnitude and sign) (a) if the net force on q_3 is 6.00 N in the $+x$-direction; (b) if the net force on q_3 is 6.00 N in the $-x$-direction?

21.67 •• Two particles having charges $q_1 = 0.530$ nC and $q_2 = 8.30$ nC are separated by a distance of 1.17 m. At what point along the line connecting the two charges is the total electric field due to the two charges equal to zero?

21.68 •• A -3.00-nC point charge is on the x-axis at $x = 1.20$ m. A second point charge, Q, is on the x-axis at -0.600 m. What must be the sign and magnitude of Q for the resultant electric field at the origin to be (a) 45.0 N/C in the $+x$-direction, (b) 45.0 N/C in the $-x$-direction?

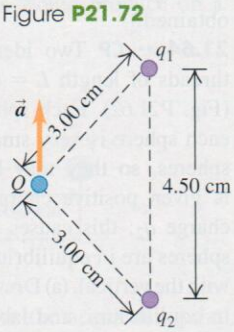
21.69 ••• A charge $+Q$ is located at the origin, and a charge $+4Q$ is at distance d away on the x-axis. Where should a third charge, q, be placed, and what should be its sign and magnitude, so that all three charges will be in equilibrium?

21.70 •• A charge of -3.00 nC is placed at the origin of an xy-coordinate system, and a charge of 2.00 nC is placed on the y-axis at $y = 4.00$ cm. (a) If a third charge, of 5.00 nC, is now placed at the point $x = 3.00$ cm, $y = 4.00$ cm, find the x- and y-components of the total force exerted on this charge by the other two charges. (b) Find the magnitude and direction of this force.

21.71 • Three identical point charges q are placed at each of three corners of a square of side L. Find the magnitude and direction of the net force on a point charge $-3q$ placed (a) at the center of the square and (b) at the vacant corner of the square. In each case, draw a free-body diagram showing the forces exerted on the $-3q$ charge by each of the other three charges.

21.72 ••• Two point charges q_1 and q_2 are held in place 4.50 cm apart. Another point charge $Q = -1.85\ \mu$C, of mass 5.50 g, is initially located 3.00 cm from both of these charges (**Fig. P21.72**) and released from rest. You observe that the initial acceleration of Q is 314 m/s^2 upward, parallel to the line connecting the two point charges. Find q_1 and q_2.

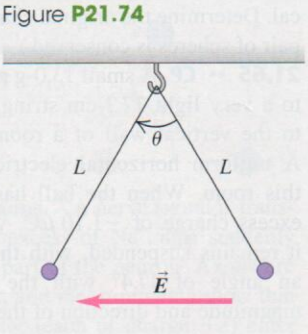
Figure **P21.72**



21.73 •• **CP Strength of the Electric Force.** Imagine two 5.0-g bags of protons, one at the earth's north pole and the other at the south pole. (a) How many protons are in each bag? (b) Calculate the gravitational attraction and the electric repulsion that each bag exerts on the other. (c) Are the forces in part (b) large enough for you to feel if you were holding one of the bags?

21.74 ••• **CP** Two tiny spheres of mass 6.80 mg carry charges of equal magnitude, 72.0 nC, but opposite sign. They are tied to the same ceiling hook by light strings of length 0.530 m. When a horizontal uniform electric field E that is directed to the left is turned on, the spheres hang at rest with the angle θ between the strings equal to 50.0° (**Fig. P21.74**). (a) Which ball (the one on the right or the one on the left) has positive charge? (b) What is the magnitude E of the field?

Figure **P21.74**



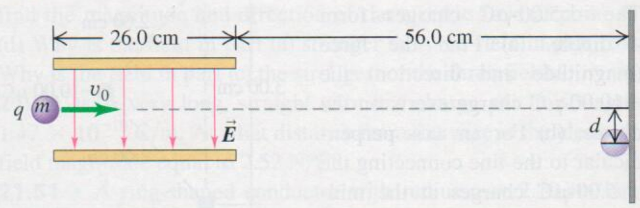
21.75 •• **CP** Consider a model of a hydrogen atom in which an electron is in a circular orbit of radius $r = 5.76 \times 10^{-11}$ m around a stationary proton. What is the speed of the electron in its orbit?

21.76 •• The earth has a downward-directed electric field near its surface of about 150 N/C. If a raindrop with a diameter of 0.020 mm is suspended, motionless, in this field, how many excess electrons must it have on its surface?

21.77 •• **CP** A proton is projected into a uniform electric field that points vertically upward and has magnitude E. The initial velocity of the proton has a magnitude v_0 and is directed at an angle α below the horizontal. (a) Find the maximum distance h_{max} that the proton descends vertically below its initial elevation. Ignore gravitational forces. (b) After what horizontal distance d does the proton return to its original elevation? (c) Sketch the trajectory of the proton. (d) Find the numerical values of h_{max} and d if $E = 500$ N/C, $v_0 = 4.00 \times 10^5$ m/s, and $\alpha = 30.0°$.

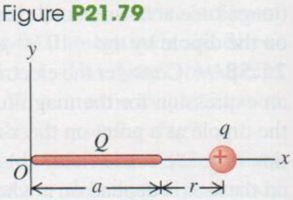
21.78 ••• A small object with mass m, charge q, and initial speed $v_0 = 5.00 \times 10^3$ m/s is projected into a uniform electric field between two parallel metal plates of length 26.0 cm (**Fig. P21.78**). The electric field between the plates is directed downward and has magnitude $E = 800$ N/C. Assume that the field is zero outside the region between the plates. The separation between the plates is large enough for the object to pass between the plates without hitting the lower plate. After passing through the field region, the object is deflected downward a vertical distance $d = 1.25$ cm from its original direction of motion and reaches a collecting plate that is 56.0 cm from the edge of the parallel plates. Ignore gravity and air resistance. Calculate the object's charge-to-mass ratio, q/m.

Figure **P21.78**



21.79 •• **CALC** Positive charge Q is distributed uniformly along the x-axis from $x = 0$ to $x = a$. A positive point charge q is located on the positive x-axis at $x = a + r$, a distance r to the right of the end of Q (**Fig. P21.79**). (a) Calculate the x- and y-components of the electric field produced by the charge distribution Q at points on the positive x-axis where $x > a$. (b) Calculate the force (magnitude and direction) that the charge distribution Q exerts on q. (c) Show that if $r \gg a$, the magnitude of the force in part (b) is approximately $Qq/4\pi\epsilon_0 r^2$. Explain why this result is obtained.

Figure **P21.79**

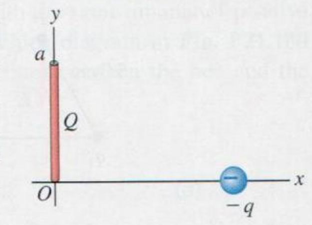


21.80 •• In a region where there is a uniform electric field that is upward and has magnitude 3.60×10^4 N/C, a small object is projected upward with an initial speed of 1.92 m/s. The object travels upward a distance of 6.98 cm in 0.200 s. What is the object's charge-to-mass ratio q/m? Assume $g = 9.80$ m/s^2, and ignore air resistance.

21.81 • A negative point charge $q_1 = -4.00$ nC is on the x-axis at $x = 0.60$ m. A second point charge q_2 is on the x-axis at $x = -1.20$ m. What must the sign and magnitude of q_2 be for the net electric field at the origin to be (a) 50.0 N/C in the $+x$-direction and (b) 50.0 N/C in the $-x$-direction?

21.82 •• CALC Positive charge Q is distributed uniformly along the positive y-axis between $y = 0$ and $y = a$. A negative point charge $-q$ lies on the positive x-axis, a distance x from the origin (**Fig. P21.82**). (a) Calculate the x- and y-components of the electric field produced by the charge distribution Q at points on the positive x-axis. (b) Calculate the x- and y-components of the force that the charge distribution Q exerts on q. (c) Show that if $x \gg a$, $F_x \cong -Qq/4\pi\epsilon_0 x^2$ and $F_y \cong +Qqa/8\pi\epsilon_0 x^3$. Explain why this result is obtained.

Figure **P21.82**



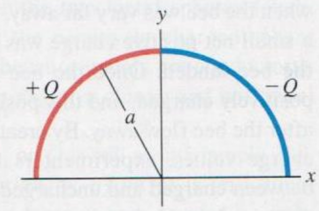
21.83 ••• A uniformly charged disk like the disk in Fig. 21.25 has radius 2.50 cm and carries a total charge of 2.0×10^{-12} C. (a) Find the electric field (magnitude and direction) on the x-axis at $x = 20.0$ cm. (b) Show that for $x \gg R$, Eq. (21.11) becomes $E = Q/4\pi\epsilon_0 x^2$, where Q is the total charge on the disk. (c) Is the magnitude of the electric field you calculated in part (a) larger or smaller than the electric field 20.0 cm from a point charge that has the same total charge as this disk? In terms of the approximation used in part (b) to derive $E = Q/4\pi\epsilon_0 x^2$ for a point charge from Eq. (21.11), explain why this is so. (d) What is the percent difference between the electric fields produced by the finite disk and by a point charge with the same charge at $x = 20.0$ cm and at $x = 10.0$ cm?

21.84 •• CP A small sphere with mass m carries a positive charge q and is attached to one end of a silk fiber of length L. The other end of the fiber is attached to a large vertical insulating sheet that has a positive surface charge density σ. Show that when the sphere is in equilibrium, the fiber makes an angle equal to $\arctan(q\sigma/2mg\epsilon_0)$ with the vertical sheet.

21.85 •• CALC Negative charge $-Q$ is distributed uniformly around a quarter-circle of radius a that lies in the first quadrant, with the center of curvature at the origin. Find the x- and y-components of the net electric field at the origin.

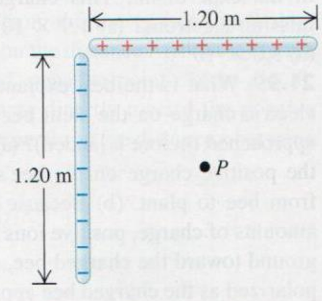
21.86 •• CALC A semicircle of radius a is in the first and second quadrants, with the center of curvature at the origin. Positive charge $+Q$ is distributed uniformly around the left half of the semicircle, and negative charge $-Q$ is distributed uniformly around the right half of the semicircle (**Fig. P21.86**). What are the magnitude and direction of the net electric field at the origin produced by this distribution of charge?

Figure **P21.86**



21.87 •• Two 1.20-m nonconducting rods meet at a right angle. One rod carries $+2.00\ \mu$C of charge distributed uniformly along its length, and the other carries $-2.00\ \mu$C distributed uniformly along it (**Fig. P21.87**). (a) Find the magnitude and direction of the electric field these rods produce at point P, which is 60.0 cm from each rod. (b) If an electron is released at P, what are the magnitude and direction of the net force that these rods exert on it?

Figure **P21.87**



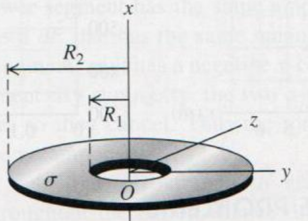
21.88 • Two very large parallel sheets are 5.00 cm apart. Sheet A carries a uniform surface charge density of $-8.80\ \mu C/m^2$, and sheet B, which is to the right of A, carries a uniform charge density of $-11.6\ \mu C/m^2$. Assume that the sheets are large enough to be treated as infinite. Find the magnitude and direction of the net electric field these sheets produce at a point (a) 4.00 cm to the right of sheet A; (b) 4.00 cm to the left of sheet A; (c) 4.00 cm to the right of sheet B.

21.89 • Repeat Problem 21.88 for the case where sheet B is positive.

21.90 • Two very large horizontal sheets are 4.25 cm apart and carry equal but opposite uniform surface charge densities of magnitude σ. You want to use these sheets to hold stationary in the region between them an oil droplet of mass 354 μg that carries an excess of five electrons. Assuming that the drop is in vacuum, (a) which way should the electric field between the plates point, and (b) what should σ be?

21.91 •• CP A thin disk with a circular hole at its center, called an *annulus*, has inner radius R_1 and outer radius R_2 (**Fig. P21.91**). The disk has a uniform positive surface charge density σ on its surface. (a) Determine the total electric charge on the annulus. (b) The annulus lies in the yz-plane, with its center at the origin. For an arbitrary point on the x-axis (the axis of the annulus), find the magnitude and direction of the electric field $\vec{E}$. Consider points both above and below the annulus. (c) Show that at points on the x-axis that are sufficiently close to the origin, the magnitude of the electric field is approximately proportional to the distance between the center of the annulus and the point. How close is "sufficiently close"? (d) A point particle with mass m and negative charge $-q$ is free to move along the x-axis (but cannot move off the axis). The particle is originally placed at rest at $x = 0.01 R_1$ and released. Find the frequency of oscillation of the particle. (*Hint:* Review Section 14.2. The annulus is held stationary.)

Figure **P21.91**

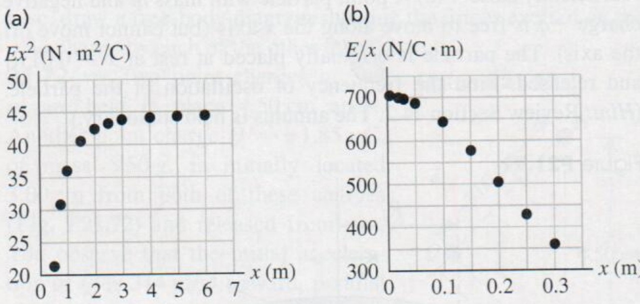


21.92 ••• DATA CP Design of an Inkjet Printer. Inkjet printers can be described as either continuous or drop-on-demand. In a continuous inkjet printer, letters are built up by squirting drops of ink at the paper from a rapidly moving nozzle. You are part of an engineering group working on the design of such a printer. Each ink drop will have a mass of 1.4×10^{-8} g. The drops will leave the nozzle and travel toward the paper at 50 m/s, passing through a charging unit that gives each drop a positive charge q by removing some electrons from it. The drops will then pass between parallel deflecting plates, 2.0 cm long, where there is a uniform vertical electric field with magnitude 8.0×10^4 N/C. Your team is working on the design of the charging unit that places the charge on the drops. (a) If a drop is to be deflected 0.30 mm by the time it reaches the end of the deflection plates, what magnitude of charge must be given to the drop? How many electrons must be removed from the drop to give it this charge? (b) If the unit that produces the stream of drops is redesigned so that it produces drops with a speed of 25 m/s, what q value is needed to achieve the same 0.30-mm deflection?

21.93 •• DATA Two small spheres, each carrying a net positive charge, are separated by 0.400 m. You have been asked to perform measurements that will allow you to determine the charge on each sphere. You set up a coordinate system with one sphere (charge q_1) at the origin and the other sphere (charge q_2) at $x = +0.400$ m. Available to you are a third sphere with net charge $q_3 = 4.00 \times 10^{-6}$ C and an apparatus that can accurately measure the location of this sphere and the net force on it. First you place the third sphere on the x-axis at $x = 0.200$ m; you measure the net force on it to be 4.50 N in the $+x$-direction. Then you move the third sphere to $x = +0.600$ m and measure the net force on it now to be 3.50 N in the $+x$-direction. (a) Calculate q_1 and q_2. (b) What is the net force (magnitude and direction) on q_3 if it is placed on the x-axis at $x = -0.200$ m? (c) At what value of x (other than $x = \pm\infty$) could q_3 be placed so that the net force on it is zero?

21.94 ••• DATA Positive charge Q is distributed uniformly around a very thin conducting ring of radius a, as in Fig. 21.23. You measure the electric field E at points on the ring axis, at a distance x from the center of the ring, over a wide range of values of x. (a) Your results for the larger values of x are plotted in **Fig. P21.94a** as Ex^2 versus x. Explain why the quantity Ex^2 approaches a constant value as x increases. Use Fig. P21.94a to calculate the net charge Q on the ring. (b) Your results for smaller values of x are plotted in Fig. P21.94b as E/x versus x. Explain why E/x approaches a constant value as x approaches zero. Use Fig. P21.94b to calculate a.

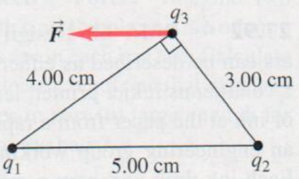
Figure **P21.94**



CHALLENGE PROBLEMS

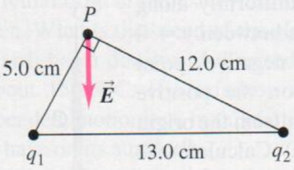
21.95 ••• Three charges are placed as shown in **Fig. P21.95.** The magnitude of q_1 is 2.00 μC, but its sign and the value of the charge q_2 are not known. Charge q_3 is +4.00 μC, and the net force $\vec{F}$ on q_3 is entirely in the negative x-direction. (a) Considering the different possible signs of q_1, there are four possible force diagrams representing the forces $\vec{F}_1$ and $\vec{F}_2$ that q_1 and q_2 exert on q_3. Sketch these four possible force configurations. (b) Using the sketches from part (a) and the direction of $\vec{F}$, deduce the signs of the charges q_1 and q_2. (c) Calculate the magnitude of q_2. (d) Determine F, the magnitude of the net force on q_3.

Figure **P21.95**



21.96 ••• Two charges are placed as shown in **Fig. P21.96.** The magnitude of q_1 is 3.00 μC, but its sign and the value of the charge q_2 are not known. The direction of the net electric field $\vec{E}$ at point P is entirely in the negative y-direction. (a) Considering the different possible signs of q_1 and q_2, four possible diagrams could represent the electric fields $\vec{E}_1$ and $\vec{E}_2$ produced by q_1 and q_2. Sketch the four possible electric-field configurations. (b) Using the sketches from part (a) and the direction of $\vec{E}$, deduce the signs of q_1 and q_2. (c) Determine the magnitude of $\vec{E}$.

Figure **P21.96**



21.97 ••• CALC Two thin rods of length L lie along the x-axis, one between $x = \frac{1}{2}a$ and $x = \frac{1}{2}a + L$ and the other between $x = -\frac{1}{2}a$ and $x = -\frac{1}{2}a - L$. Each rod has positive charge Q distributed uniformly along its length. (a) Calculate the electric field produced by the second rod at points along the positive x-axis. (b) Show that the magnitude of the force that one rod exerts on the other is

$$F = \frac{Q^2}{4\pi\epsilon_0 L^2}\ln\left[\frac{(a+L)^2}{a(a+2L)}\right]$$

(c) Show that if $a \gg L$, the magnitude of this force reduces to $F = Q^2/4\pi\epsilon_0 a^2$. (*Hint:* Use the expansion $\ln(1+z) = z - \frac{1}{2}z^2 + \frac{1}{3}z^3 - \cdots$, valid for $|z| \ll 1$. Carry *all* expansions to at least order L^2/a^2.) Interpret this result.

PASSAGE PROBLEMS

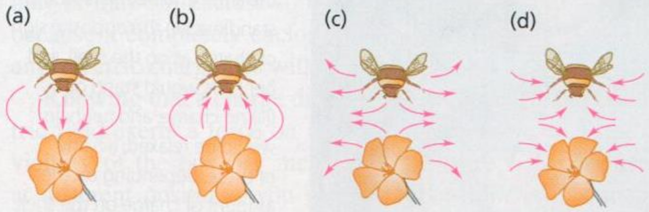
BIO ELECTRIC BEES. Flying insects such as bees may accumulate a small positive electric charge as they fly. In one experiment, the mean electric charge of 50 bees was measured to be $+(30 \pm 5)$ pC per bee. Researchers also observed the electrical properties of a plant consisting of a flower atop a long stem. The charge on the stem was measured as a positively charged bee approached, landed, and flew away. Plants are normally electrically neutral, so the measured net electric charge on the stem was zero when the bee was very far away. As the bee approached the flower, a small net positive charge was detected in the stem, even before the bee landed. Once the bee landed, the whole plant became positively charged, and this positive charge remained on the plant after the bee flew away. By creating artificial flowers with various charge values, experimenters found that bees can distinguish between charged and uncharged flowers and may use the positive electric charge left by a previous bee as a cue indicating whether a plant has already been visited (in which case, little pollen may remain).

21.98 Consider a bee with the mean electric charge found in the experiment. This charge represents roughly how many missing electrons? (a) 1.9×10^8; (b) 3.0×10^8; (c) 1.9×10^{18}; (d) 3.0×10^{18}.

21.99 What is the best explanation for the observation that the electric charge on the stem became positive as the charged bee approached (before it landed)? (a) Because air is a good conductor, the positive charge on the bee's surface flowed through the air from bee to plant. (b) Because the earth is a reservoir of large amounts of charge, positive ions were drawn up the stem from the ground toward the charged bee. (c) The plant became electrically polarized as the charged bee approached. (d) Bees that had visited the plant earlier deposited a positive charge on the stem.

21.100 After one bee left a flower with a positive charge, that bee flew away and another bee with the same amount of positive charge flew close to the plant. Which diagram in **Fig. P21.100** best represents the electric field lines between the bee and the flower?

Figure **P21.100**



21.101 In a follow-up experiment, a charge of +40 pC was placed at the center of an artificial flower at the end of a 30-cm-long stem. Bees were observed to approach no closer than 15 cm from the center of this flower before they flew away. This observation suggests that the smallest external electric field to which bees may be sensitive is closest to which of these values? (a) 2.4 N/C; (b) 16 N/C; (c) 2.7×10^{-10} N/C; (d) 4.8×10^{-10} N/C.

Answers

Chapter Opening Question ?

(ii) Water molecules have a permanent electric dipole moment: One end of the molecule has a positive charge and the other end has a negative charge. These ends attract negative and positive ions, respectively, holding the ions apart in solution. Water is less effective as a solvent for materials whose molecules do not ionize (called *nonionic* substances), such as oils.

Test Your Understanding Questions

21.1 (iv) Two charged objects repel if their charges are of the same sign (either both positive or both negative).

21.2 (a) (i), (b) (ii) Before the two spheres touch, the negatively charged sphere exerts a repulsive force on the electrons in the other sphere, causing zones of positive and negative induced charge (see Fig. 21.7b). The positive zone is closer to the negatively charged sphere than the negative zone, so there is a net force of attraction that pulls the spheres together, like the comb and insulator in Fig. 21.8b. Once the two metal spheres touch, some of the excess electrons on the negatively charged sphere will flow onto the other sphere (because metals are conductors). Then both spheres will have a net negative charge and will repel each other.

21.3 (iv) The force exerted by q_1 on Q is still as in Example 21.4. The magnitude of the force exerted by q_2 on Q is still equal to $F_{1 \text{ on } Q}$, but the direction of the force is now *toward* q_2 at an angle α below the x-axis. Hence the x-components of the two forces cancel while the (negative) y-components add together, and the total electric force is in the negative y-direction.

21.4 (a) (ii), (b) (i) The electric field $\vec{E}$ produced by a positive point charge points directly away from the charge (see Fig. 21.18a) and has a magnitude that depends on the distance r from the charge to the field point. Hence a second, negative point charge $q < 0$ will feel a force $\vec{F} = q\vec{E}$ that points directly toward the positive charge and has a magnitude that depends on the distance r between the two charges. If the negative charge moves directly toward the positive charge, the direction of the force remains the same but the force magnitude increases as the distance r decreases. If the negative charge moves in a circle around the positive charge, the force magnitude stays the same (because the distance r is constant) but the force direction changes.

21.5 (iv) Think of a pair of segments of length dy, one at coordinate $y > 0$ and the other at coordinate $-y < 0$. The upper segment has a positive charge and produces an electric field $d\vec{E}$ at P that points away from the segment, so this $d\vec{E}$ has a positive x-component and a negative y-component, like the vector $d\vec{E}$ in Fig. 21.24. The lower segment has the same amount of negative charge. It produces a $d\vec{E}$ that has the same magnitude but points *toward* the lower segment, so it has a negative x-component and a negative y-component. By symmetry, the two x-components are equal but opposite, so they cancel. Thus the total electric field has only a negative y-component.

21.6 yes If the field lines are straight, $\vec{E}$ must point in the same direction throughout the region. Hence the force $\vec{F} = q\vec{E}$ on a particle of charge q is always in the same direction. A particle released from rest accelerates in a straight line in the direction of $\vec{F}$, and so its trajectory is a straight line along a field line.

21.7 (ii) Equations (21.17) and (21.18) tell us that the potential energy for a dipole in an electric field is $U = -\vec{p} \cdot \vec{E} = -pE\cos\phi$, where ϕ is the angle between the directions of $\vec{p}$ and $\vec{E}$. If $\vec{p}$ and $\vec{E}$ point in opposite directions, so that $\phi = 180°$, we have $\cos\phi = -1$ and $U = +pE$. This is the maximum value that U can have. From our discussion of energy diagrams in Section 7.5, it follows that this is a situation of unstable equilibrium.

Bridging Problem

$E = 2kQ/\pi a^2$ in the $-y$-direction

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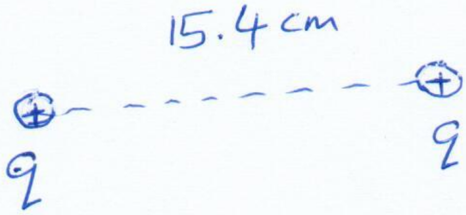
Physics Department

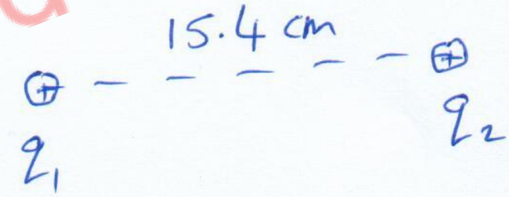
Physics (102) – Solutions for Suggested Problems
chapter 21 / Sear and Zemansky / 14^{th} edition
Prof. Mahmoud Jaghoub

9]



a) $F = k \frac{q^2}{r^2}$ since chages are the same

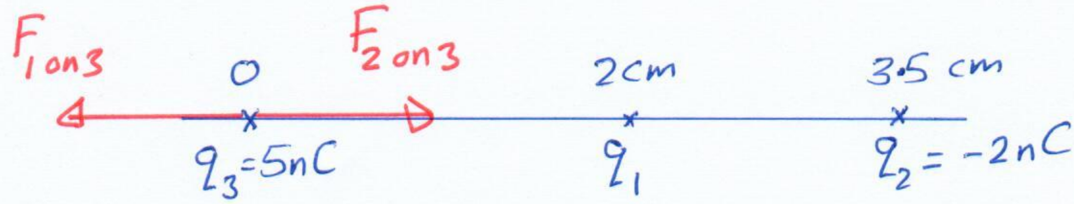
$0.205 = 9\times10^{9} \frac{q^2}{(15.4\times10^{-2})^2} \Rightarrow q \approx 735\times10^{-9}\,C$
$= 735\,nC$



b) $q_1 = 4q_2$

$0.205 = \frac{9\times10^{9}(4q_2)(q_2)}{(15.4\times10^{-2})^2} \Rightarrow q_2 = 0.367\,\mu C$

$\therefore q_1 = 4q_2 = 1.47\,\mu C$



For the net force on q_3 to be zero $\Rightarrow$ q_1 must exert a force equal in magnitude and opposite in direction to F_{2on3} $\Rightarrow$ F_1 is to the left $\Rightarrow$ charge q_1 must be positive.

$F_{1on3} = F_{2on3}$ as shown above

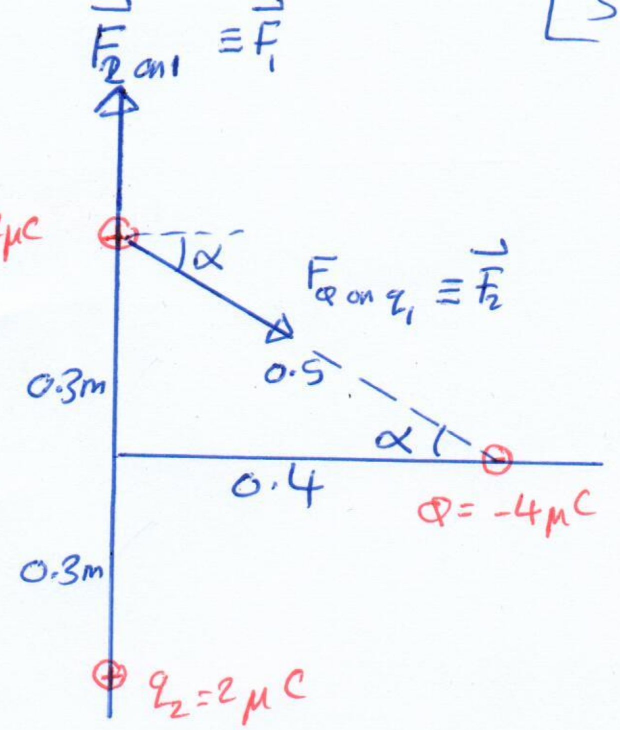
$$k\frac{|q_2 q_3|}{(3.5\times10^{-2})^2} = k\frac{|q_1 q_3|}{(2\times10^{-2})^2}$$

$$\Rightarrow \frac{|q_2|}{(3.5)^2} = \frac{|q_1|}{(2)^2} \Rightarrow$$

$$q_1 = \frac{(2)^2}{(3.5)^2}|q_2| \simeq 0.65\,nC.$$

Note the point $x=0$ (the origin) is an equilibrium point where $E_{net} = 0$.

16]



$$F_1 = \frac{9\times10^9 \times (2\times10^{-6})^2}{(0.6)^2} \ N/C$$

$$\vec{F}_1 = 0.1\,\hat{j} \quad N/C$$

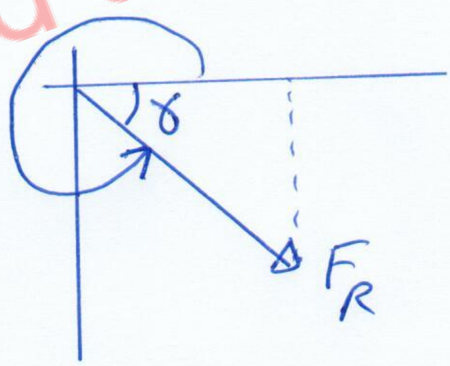
$$F_2 = \frac{9\times10^9\,(2\times10^{-6})(4\times10^{-6})}{(0.5)^2}$$

$$= 0.288 \ N/C$$

$$\vec{F}_2 = 0.288\cos\alpha\,\hat{i} - 0.288\sin\alpha\,\hat{j}$$

$$= 0.230\,\hat{i} - 0.173\,\hat{j}$$

$$\vec{F}_R = 0.230\,\hat{i} - 0.073\,\hat{j}$$



$$\tan\gamma = \left|\frac{-0.073}{0.230}\right|$$

$$\gamma \sim 17.6^\circ$$

$$\theta = 360^\circ - 17.6^\circ = 342.4^\circ.$$

$$|\vec{F}_R| = \sqrt{F_{Rx}^2 + F_{Ry}^2}$$

L4

23 $E = 2950\ N/C$

a) $F = qE = (1.6\times10^{-19})(2950) = 4.72\times10^{-16}\ N.$

b) $F = m_e a \Rightarrow a = \dfrac{F}{m_e} = \dfrac{4.72\times10^{-16}}{1.67\times10^{-27}} \approx 2.83\times10^{11}\ m/s^2$

c) Constant acceleration $\Rightarrow$ use equations of motion.

$$v_f = v_i + at = 0 + (2.83\times10^{11})(1.8\times10^{-6})$$
$$= 509400\ m/s$$

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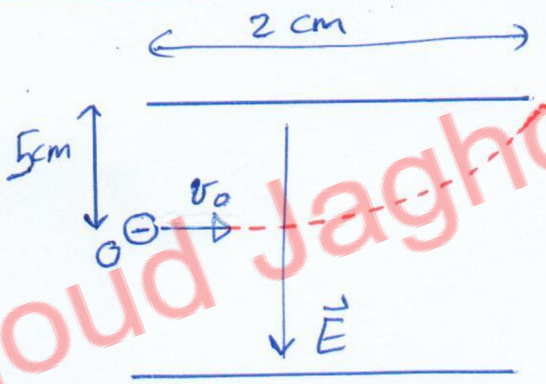
29 (a)



Electric force acting on the e^- is OPPOSITE to the electric field i.e vertically upwards.

$v_0 = 2\times10^6\ m/s.$

uniform $\vec{E}$ field $\Rightarrow$ constant upward acceleration.

Take the e^- to be initially at the origin (point O).

$$a = \frac{qE}{m} = \frac{1.6\times10^{-19}}{9.11\times10^{-31}} E = 1.756\times10^{11} E \quad m/s^2.$$ vertically upwards.

$+\uparrow$ $y_f - y_i = v_{iy} t + \frac{1}{2} a t^2$

$y_f - y_i = 0 + \frac{1}{2} a t^2$ since initial speed along y-direction is zero.

Now motion along x-direction:

$\rightarrow +$ $x_f - x_i = v_{ix} t$ (no acceleration along x-direction)

$\Rightarrow t = \frac{x_f - x_i}{v_{ix}}$

Substitute for t in the equation for the vertical motion:

$y_f - y_i = \frac{1}{2} a \frac{(x_f - x_i)^2}{v_{ix}^2}$

$y_f - y_i = \frac{1}{2} a \frac{(x_f - x_i)^2}{v_0^2}$ (initial speed v_0 along x-axis)

$\therefore y_f - y_i = \frac{1}{2} (1.756 \times 10^{11} E) \frac{(x_f - x_i)^2}{v_0^2}$

$0.05 - 0 = \frac{1.756 \times 10^{11}}{2} \frac{(0.02 - 0)^2}{(2 \times 10^6)^2} E$

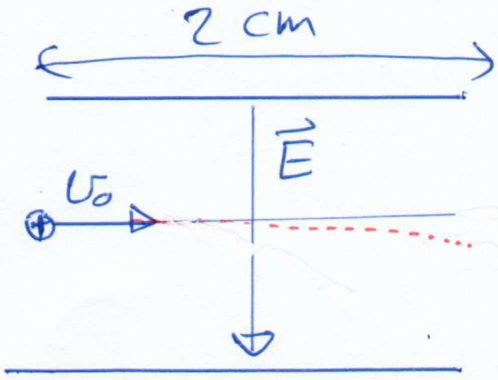
$\therefore E \approx 5695$ N/C

(b) For a proton two differences from the above occur

(i) the acceleration is downwards along the E-field

(ii) the magnitude of the acceleration is smaller as the protons mass is larger.

For proton:



$$a = \frac{qE}{m_p}$$

$$= \frac{(1.6\times10^{-19})E}{1.67\times10^{-27}}$$

$$a \approx 96\times10^{6}\, E \ \ m/s^2 = 5.4672\times10^{11}\ N/C$$

How long would the proton take to cover a ~~dist~~ horizontal distance of 2 cm (that is to exit the region of the electric field between the plates?

$$x_f - x_i = v_{ix} t \quad \text{(no acceleration along } x\text{-direction)}$$

$$0.02 - 0 = 2\times10^{6}\, t \Rightarrow t = \frac{0.02}{2\times10^{6}} = 1\times10^{-8}\ s$$

$$t = 10\times10^{-9}\, s = 10\ ns.$$

what is the vertical distance covered by the proton as it exits the E-field?

$$\downarrow +\quad y_f - y_i = v_{iy} t + \frac{1}{2} a t^2$$

$$y_f - 0 = 0 + \frac{1}{2}(5.4672\times10^{11})(10\times10^{-9})^2$$

$$\approx 2.73\times10^{-5}\ m = 2.73\times10^{-2}\ mm$$

$$y_f \sim 0.00273\ mm$$

(c) The vertical distance travelled by the electron as it exis the E-field is larger thant that of the proton as the electron's acceleration is much higher (larger).

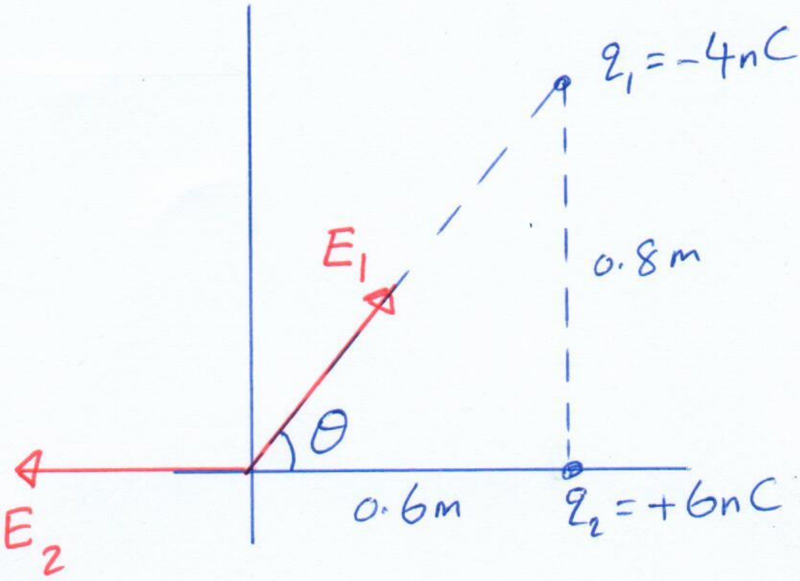
(d) The effect of the gravitational force acting on each of the e^- and the proton is $<<$ than the electric force $\Rightarrow$ reasonable to ignore the gravitational force for both.

48

$$E_2 = \frac{9\times10^9(6\times10^{-9})}{(0.6)^2}$$

$$= 150\ N/C$$

$$\vec{E}_2 = -150\,\hat{i}$$



$$E_1 = \frac{9\times10^9(4\times10^{-9})}{(1)^2}$$

$$= 36\ N/C$$

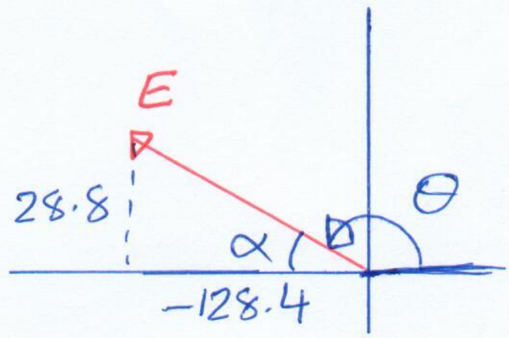
$$\vec{E}_1 = E_1\cos\theta\,\hat{i} + E_1\sin\theta\,\hat{j}$$

$$= 36\times0.6\,\hat{i} + 36\times0.8\,\hat{j}$$

$$\vec{E}_1 = 21.6\,\hat{i} + 28.8\,\hat{j}$$

$$\Rightarrow \vec{E}_R = \vec{E}_1 + \vec{E}_2 = -128.4\,\hat{i} + 28.8\,\hat{j}$$ (second quadrant)

$$\tan\alpha = \left|\frac{E_y}{E_x}\right| = \frac{28.8}{128.4}$$

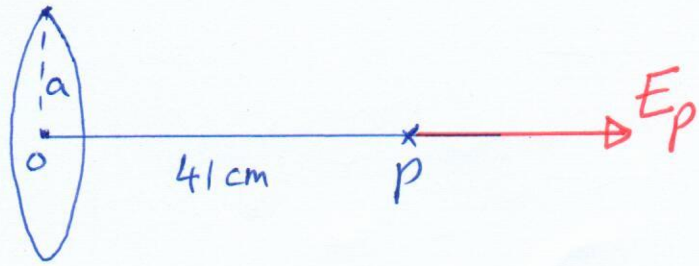


$$\Rightarrow \alpha \simeq 12.6^\circ$$

$$\theta = 180 - \alpha = 167.4^\circ.$$

$$E_R = \sqrt{E_{Rx}^2 + E_{Ry}^2} \approx 131.6\ N/C.$$

51]



(a)

$a = 2.1\ cm$; $Q = 0.129\ nC$

$$\lambda = \frac{Q}{L} = \frac{0.129\ nC}{2\pi a} = \frac{0.129}{2\pi(2.1\times10^{-2})} \approx 0.98\ nC/m$$

due to symmetry E field is along the x-axis towards the right as the charge is positive.

$$E_p = k\frac{xQ}{(a^2+x^2)^{3/2}} = \frac{9\times10^9(41\times10^{-2})(0.129\times10^{-9})}{((2.1\times10^{-2})^2+(41\times10^{-2})^2)^{3/2}}$$

$\therefore E_p \sim 6.88\ N/C$.

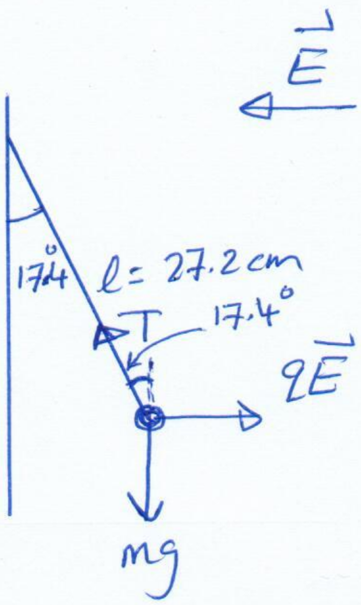
(b) The force exerted by the charge q on the ring equals the force exerted by the ring on the charge q (action-reaction forces according to Newton's third law).

$$\vec{F} = q\vec{E} = (-3\times10^{-6})(6.88\hat{i}) = -20.64\times10^{-6}\hat{i}$$

this is force from ring on charge q ⇒ force of charge q on ring is

$$\vec{F} = +20.64\times10^{-6}\hat{i}$$

65] since q is negative the force acting on it is opposite to the field.



$\xrightarrow{+}$ $qE - T\sin 17.4^\circ = 0$

$$qE = T\sin 17.4^\circ \quad -(1)$$

$\overset{+}{\uparrow}$ $T\cos 17.4^\circ - mg = 0$

$$\therefore \; mg = T\cos 17.4^\circ \quad -(2)$$

$$(1)/(2) \Rightarrow \frac{qE}{mg} = \tan 17.4^\circ$$

$$E = \frac{mg}{q}\tan 17.4^\circ$$

$$= \frac{13\times10^{-3}\times 9.8}{1.1\times10^{-6}}\tan 17.4^\circ$$

$$= 36295 \text{ N/C}.$$