any) in (b) its kinetic energy and (c) the electric potential energy of the proton-field system.
3. When charged particles are separated by an infinite distance, the electric potential energy of the pair is zero. When the particles are brought close, the electric potential energy of a pair with the same sign is positive, whereas the electric potential energy of a pair with opposite signs is negative. Give a physical explanation of this statement.
4. Describe the equipotential surfaces for (a) an infinite line of charge and (b) a uniformly charged sphere.
5. What determines the maximum electric potential to which the dome of a Van de Graaff generator can be raised?
6. Study Figure 23.3 and the accompanying text discussion of charging by induction. When the grounding wire is touched to the rightmost point on the sphere in Figure 23.3c, electrons are drained away from the sphere to leave the sphere positively charged. Suppose the grounding wire is touched to the leftmost point on the sphere instead. (a) Will electrons still drain away, moving closer to the negatively charged rod as they do so? (b) What kind of charge, if any, remains on the sphere?

## Problems

WebAssign The problems found in this chapter may be assigned online in Enhanced WebAssign

1. denotes straightforward problem; 2. denotes intermediate problem; 3. denotes challenging problem
2. full solution available in the Student Solutions Manual/Study Guide
3. denotes problems most often assigned in Enhanced WebAssign; these provide students with targeted feedback and either a Master It tutorial or a Watch It solution video.

Q|C denotes asking for quantitative and conceptual reasoning
S denotes symbolic reasoning problem
M denotes Master It tutorial available in Enhanced WebAssign
GP denotes guided problem
shaded denotes "paired problems" that develop reasoning with symbols and numerical values

## Section 25.1 Electric Potential and Potential Difference

## Section 25.2 Potential Difference in a Uniform Electric Field

1. M (a) Calculate the speed of a proton that is accelerated from rest through an electric potential difference of 120 V . (b) Calculate the speed of an electron that is accelerated through the same electric potential difference.
2. How much work is done (by a battery, generator, or some other source of potential difference) in moving Avogadro's number of electrons from an initial point where the electric potential is 9.00 V to a point where the electric potential is -5.00 V ? (The potential in each case is measured relative to a common reference point.)
3. A uniform electric field of magnitude $325 \mathrm{~V} / \mathrm{m}$ is directed in the negative $y$ direction in Figure P25.3. The coordinates of point (A) are $(-0.200,-0.300) \mathrm{m}$, and those of point (B) are $(0.400$, $0.500) \mathrm{m}$. Calculate the electric potential difference $V_{\circledR}-V_{\circledast}$ using the dashed-line path.
4. $\mathbf{Q} \mid \mathbf{C}$ (a) Find the electric potential difference $\Delta V_{e}$ required to stop an electron (called a "stopping potential") moving with an initial speed of $2.85 \times 10^{7} \mathrm{~m} / \mathrm{s}$. (b) Would a proton traveling at the same speed require a greater or lesser magnitude of electric potential difference? Explain. (c) Find a symbolic expression for the ratio of the proton stopping potential and the electron stopping potential, $\Delta V_{p} / \Delta V_{e}$.
5. M An electron moving parallel to the $x$ axis has an initial speed of $3.70 \times 10^{6} \mathrm{~m} / \mathrm{s}$ at the origin. Its speed is reduced to $1.40 \times 10^{5} \mathrm{~m} / \mathrm{s}$ at the point $x=2.00 \mathrm{~cm}$. (a) Calculate
the electric potential difference between the origin and that point. (b) Which point is at the higher potential?
6. $\mathbf{Q} \mid \mathbf{C} \mathbf{S}$ Starting with the definition of work, prove that at every point on an equipotential surface, the surface must be perpendicular to the electric field there.
7. A particle having charge $q=+2.00 \mu \mathrm{C}$ and mass $m=$ 0.0100 kg is connected to a string that is $L=1.50 \mathrm{~m}$ long and tied to the pivot point $P$ in Figure P25.7. The particle, string, and pivot point all lie on a frictionless, horizontal table. The particle is released from rest when the string makes an angle $\theta=60.0^{\circ}$ with a uniform electric field of magnitude $E=300 \mathrm{~V} / \mathrm{m}$. Determine the speed of the particle when the string is parallel to the electric field.


Figure P25.7
8. GP Q|C Review. A block having mass $m$ and charge $+Q$ is connected to an insulating spring having a force constant $k$. The block lies on a frictionless, insulating, horizontal track, and the system is immersed in a uniform electric field of magnitude $E$ directed as shown in Figure P25.8 (page 734). The block is released from rest when the spring is unstretched (at $x=0$ ). We wish to show that the ensuing motion of the block is simple harmonic. (a) Consider the system of the block, the spring, and the electric field. Is this system isolated or nonisolated? (b) What kinds of potential energy
exist within this system? (c) Call the initial configuration of the system that existing just as the block is released from rest. The final configuration is when the block momentarily comes to rest again. What is the value of $x$


Figure P25.8 when the block comes to rest momentarily? (d) At some value of $x$ we will call $x=x_{0}$, the block has zero net force on it. What analysis model describes the particle in this situation? (e) What is the value of $x_{0}$ ? (f) Define a new coordinate system $x^{\prime}$ such that $x^{\prime}=x-x_{0}$. Show that $x^{\prime}$ satisfies a differential equation for simple harmonic motion. (g) Find the period of the simple harmonic motion. (h) How does the period depend on the electric field magnitude?
9. $\mathbf{Q} \mid \mathbf{C}$ An insulating rod having linear charge density $\lambda=40.0 \mu \mathrm{C} / \mathrm{m}$ and linear mass density $\mu=0.100 \mathrm{~kg} / \mathrm{m}$ is released from rest in a uniform electric field $E=100 \mathrm{~V} / \mathrm{m}$ directed perpendicular to the rod (Fig. P25.9). (a) Determine the speed of the rod after it has traveled 2.00 m . (b) What If? How does your answer to part (a) change if the


Figure P25.9 electric field is not perpendicular to the rod? Explain.

Section 25.3 Electric Potential and Potential Energy Due to Charged Particles

Note: Unless stated otherwise, assume the reference level of potential is $V=0$ at $r=\infty$.
10. $\mathbf{Q} \mid \mathbf{C}$ (a) Calculate the electric potential 0.250 cm from an electron. (b) What is the electric potential difference between two points that are 0.250 cm and 0.750 cm from an electron? (c) How would the answers change if the electron were replaced with a proton?
11. Two point charges are on the $y$ axis. A $4.50-\mu \mathrm{C}$ charge is located at $y=1.25 \mathrm{~cm}$, and a $-2.24-\mu \mathrm{C}$ charge is located at $y=-1.80 \mathrm{~cm}$. Find the total electric potential at (a) the origin and (b) the point whose coordinates are $(1.50 \mathrm{~cm}, 0)$.
12. The two charges in Figure P25.12 are separated by $d=$ 2.00 cm . Find the electric potential at (a) point $A$ and (b) point $B$, which is halfway between the charges.
13. S Three positive charges are located at the corners of an equilateral triangle as in Figure P25.13. Find an expression for the electric potential at the center of the triangle.
14. Q|C Two charged particles, $Q_{1}=$ +5.00 nC and $Q_{2}=-3.00 \mathrm{nC}$, are separated by 35.0 cm . (a) What is the electric potential energy of the pair? Explain the significance of the alge-


Figure P25.12


Figure P25.13
braic sign of your answer. (b) What is the electric potential at a point midway between the charged particles?
15. Given two particles with $2.00-\mu \mathrm{C}$ charges as shown in Figure P25.15 and a particle with charge $q=1.28 \times 10^{-18} \mathrm{C}$ at the origin, (a) what is the net force exerted by the two $2.00-\mu \mathrm{C}$ charges on the test charge $q$ ? (b) What is the electric field at the origin due to the two $2.00-\mu \mathrm{C}$ particles? (c) What is the electric potential at the origin due to the two $2.00-\mu \mathrm{C}$ particles?


Figure P25.15
16. The two charges in Figure P25.16 are separated by a distance $d=2.00 \mathrm{~cm}$, and $Q=$ +5.00 nC . Find (a) the electric potential at $A$, (b) the electric potential at $B$, and (c) the electric potential difference between $B$ and $A$.
17. S Four point charges each having charge $Q$ are located at the corners of a square having sides of length $a$.


Figure P25.16 Find expressions for (a) the total electric potential at the center of the square due to the four charges and (b) the work required to bring a fifth charge $q$ from infinity to the center of the square.
18. M At a certain distance from a charged particle, the magnitude of the electric field is $500 \mathrm{~V} / \mathrm{m}$ and the electric potential is -3.00 kV . (a) What is the distance to the particle? (b) What is the magnitude of the charge?
19. A particle with charge $+q$ is at the origin. A particle with charge $-2 q$ is at $x=2.00 \mathrm{~m}$ on the $x$ axis. (a) For what finite value(s) of $x$ is the electric field zero? (b) For what finite value(s) of $x$ is the electric potential zero?
20. M The three charged particles in Figure P25.20 are at the vertices of an isosceles triangle (where $d=2.00 \mathrm{~cm}$ ). Taking $q=7.00 \mu \mathrm{C}$, calculate the electric potential at point $A$, the midpoint of the base.
21. Two particles each with charge $+2.00 \mu \mathrm{C}$ are located on the $x$ axis. One is at $x=1.00 \mathrm{~m}$, and the other is at $x=-1.00 \mathrm{~m}$. (a) Determine the electric potential on the $y$ axis at


Figure P25.20 $y=0.500 \mathrm{~m}$. (b) Calculate the change in electric potential energy of the system as a third charged particle of $-3.00 \mu \mathrm{C}$ is brought from infinitely far away to a position on the $y$ axis at $y=0.500 \mathrm{~m}$.
22. S Show that the amount of work required to assemble four identical charged particles of magnitude $Q$ at the corners of a square of side $s$ is $5.41 k_{e} Q^{2} / s$.
23. Four identical charged particles $(q=+10.0 \mu \mathrm{C})$ are located on the corners of a rectangle as shown in Figure P25.23. The dimensions of the rectangle are $L=60.0 \mathrm{~cm}$ and $W=15.0 \mathrm{~cm}$. Calculate the change in electric potential energy of the system as the particle at the lower left


Figure P25.23 corner in Figure P25.23 is brought to this position from infinitely far away. Assume the other three particles in Figure P25.23 remain fixed in position.
24. S Two charged particles of equal magnitude are located along the $y$ axis equal distances above and below the $x$ axis as shown in Figure P25.24. (a) Plot a graph of the electric potential at points along the $x$ axis over the interval $-3 a<x<3 a$. You should plot the potential in units of $k_{e} Q / a$. (b) Let the charge of the particle located at $y=-a$ be negative. Plot the potential along the $y$ axis over the interval


Figure P25.24 $-4 a<y<4 a$.
25. S Five particles with equal negative charges $-q$ are placed symmetrically around a circle of radius $R$. Calculate the electric potential at the center of the circle.
26. S Three particles with equal positive charges $q$ are at the corners of an equilateral triangle of side $a$ as shown in Figure P25.26. (a) At what point, if any, in the plane of the particles is the electric potential zero? (b) What is the electric potential at the position of one of the particles due to the other two particles in the triangle?


Figure P25.26
27. Q|C Review. Two insulating spheres have radii 0.300 cm and 0.500 cm , masses 0.100 kg and 0.700 kg , and uniformly distributed charges $-2.00 \mu \mathrm{C}$ and $3.00 \mu \mathrm{C}$. They are released from rest when their centers are separated by 1.00 m . (a) How fast will each be moving when they collide? (b) What If? If the spheres were conductors, would the speeds be greater or less than those calculated in part (a)? Explain.
28. $\mathbf{Q} \mid \mathbf{C} \boldsymbol{S}$ Review. Two insulating spheres have radii $r_{1}$ and $r_{2}$, masses $m_{1}$ and $m_{2}$, and uniformly distributed charges $-q_{1}$ and $q_{2}$. They are released from rest when their centers are separated by a distance $d$. (a) How fast is each moving when they collide? (b) What If? If the spheres were conductors, would their speeds be greater or less than those calculated in part (a)? Explain.
29. S How much work is required to assemble eight identical charged particles, each of magnitude $q$, at the corners of a cube of side $s$ ?
30. S Review. A light, unstressed spring has length $d$. Two identical particles, each with charge $q$, are connected to the opposite ends of the spring. The particles are held stationary a distance $d$ apart and then released at the same moment. The system then oscillates on a frictionless, horizontal table. The spring has a bit of internal kinetic friction,
so the oscillation is damped. The particles eventually stop vibrating when the distance between them is $3 d$. Assume the system of the spring and two charged particles is isolated. Find the increase in internal energy that appears in the spring during the oscillations.
31. In 1911, Ernest Rutherford and his assistants Geiger and Marsden conducted an experiment in which they scattered alpha particles (nuclei of helium atoms) from thin sheets of gold. An alpha particle, having charge $+2 e$ and mass $6.64 \times 10^{-27} \mathrm{~kg}$, is a product of certain radioactive decays. The results of the experiment led Rutherford to the idea that most of an atom's mass is in a very small nucleus, with electrons in orbit around it. (This is the planetary model of the atom, which we'll study in Chapter 42.) Assume an alpha particle, initially very far from a stationary gold nucleus, is fired with a velocity of $2.00 \times 10^{7} \mathrm{~m} / \mathrm{s}$ directly toward the nucleus (charge $+79 e$ ). What is the smallest distance between the alpha particle and the nucleus before the alpha particle reverses direction? Assume the gold nucleus remains stationary.
32. S Four identical particles, each having charge $q$ and mass $m$, are released from rest at the vertices of a square of side $L$. How fast is each particle moving when their distance from the center of the square doubles?

## Section 25.4 Obtaining the Value of the Electric Field from the Electric Potential

33. The potential in a region between $x=0$ and $x=6.00 \mathrm{~m}$ is $V=a+b x$, where $a=10.0 \mathrm{~V}$ and $b=-7.00 \mathrm{~V} / \mathrm{m}$. Determine (a) the potential at $x=0,3.00 \mathrm{~m}$, and 6.00 m and (b) the magnitude and direction of the electric field at $x=$ $0,3.00 \mathrm{~m}$, and 6.00 m .
34. Figure P25.34 represents a graph of the electric potential in a region of space versus position $x$, where the electric field is parallel to the $x$ axis. Draw a graph of the $x$ component of the electric field versus $x$ in this region.


Figure P25.34
35. Over a certain region of space, the electric potential is $V=$ $5 x-3 x^{2} y+2 y z^{2}$. (a) Find the expressions for the $x, y$, and $z$ components of the electric field over this region. (b) What is the magnitude of the field at the point $P$ that has coordinates ( $1.00,0,-2.00$ ) m?
36. An electric field in a region of space is parallel to the $x$ axis. The electric potential varies with position as shown in Figure P25.36. Graph the $x$ component of the electric field versus position in this region of space.


Figure P25.36
37. S The electric potential inside a charged spherical conductor of radius $R$ is given by $V=k_{e} Q / R$, and the potential outside is given by $V=k_{e} Q / r$. Using $E_{r}=-d V / d r$, derive the electric field (a) inside and (b) outside this charge distribution.
38. Q|C Figure P25.38 shows several equipotential lines, each labeled by its potential in volts. The distance between the lines of the square grid represents 1.00 cm . (a) Is the magnitude of the field larger at $A$ or at $B$ ? Explain how you can tell. (b) Explain what you can determine about $\overrightarrow{\mathbf{E}}$ at $B$. (c) Represent what the electric field looks like by drawing at


Numerical values are in volts.
Figure P25.38 least eight field lines.
S It is shown in Example 25.7 that the potential at a point $P$ a distance $a$ above one end of a uniformly charged rod of length $\ell$ lying along the $x$ axis is

$$
V=k_{e} \frac{Q}{\ell} \ln \left(\frac{\ell+\sqrt{a^{2}+\ell^{2}}}{a}\right)
$$

Use this result to derive an expression for the $y$ component of the electric field at $P$.

## Section 25.5 Electric Potential Due to Continuous Charge Distributions

40. A uniformly charged insulating rod of length 14.0 cm is bent into the shape of a semicircle as shown in Figure P25.40. The rod has a total charge of $-7.50 \mu \mathrm{C}$. Find the electric potential at $O$, the center of the semicircle.


Figure P25.40
41. S. Consider a ring of radius $R$ with the total charge $Q$ spread uniformly over its perimeter. What is the potential difference between the point at the center of the ring and a point on its axis a distance $2 R$ from the center?
42. S A rod of length $L$ (Fig. P25.42) lies along the $x$ axis with its left end at the origin. It has a nonuniform charge density $\lambda=\alpha x$, where $\alpha$ is a positive constant. (a) What are the units of $\alpha$ ? (b) Calculate the electric potential at $A$.
43. S For the arrangement described in Problem 42, cal-


Figure P25.42
Problems 42 and 43. culate the electric potential at point $B$, which lies on the perpendicular bisector of the rod a distance $b$ above the $x$ axis.
44. S A wire having a uniform linear charge density $\lambda$ is bent into the shape shown in Figure P25.44. Find the electric potential at point $O$.


Figure P25.44

## Section 25.6 Electric Potential Due to a Charged Conductor

45. How many electrons should be removed from an initially uncharged spherical conductor of radius 0.300 m to produce a potential of 7.50 kV at the surface?
46. The electric field magnitude on the surface of an irregularly shaped conductor varies from $56.0 \mathrm{kN} / \mathrm{C}$ to $28.0 \mathrm{kN} / \mathrm{C}$. Can you evaluate the electric potential on the conductor? If so, find its value. If not, explain why not.
47. Electric charge can accumulate on an airplane in flight. You may have observed needle-shaped metal extensions on the wing tips and tail of an airplane. Their purpose is to allow charge to leak off before much of it accumulates. The electric field around the needle is much larger than the field around the body of the airplane and can become large enough to produce dielectric breakdown of the air, discharging the airplane. To model this process, assume two charged spherical conductors are connected by a long conducting wire and a $1.20-\mu \mathrm{C}$ charge is placed on the combination. One sphere, representing the body of the airplane, has a radius of 6.00 cm ; the other, representing the tip of the needle, has a radius of 2.00 cm . (a) What is the electric potential of each sphere? (b) What is the electric field at the surface of each sphere?
48. M A spherical conductor has a radius of 14.0 cm and a charge of $26.0 \mu \mathrm{C}$. Calculate the electric field and the electric potential at (a) $r=10.0 \mathrm{~cm}$, (b) $r=20.0 \mathrm{~cm}$, and (c) $r=$ 14.0 cm from the center.

## Section 25.8 Applications of Electrostatics

49. M Lightning can be studied with a Van de Graaff generator, which consists of a spherical dome on which charge is continuously deposited by a moving belt. Charge can be added until the electric field at the surface of the dome becomes equal to the dielectric strength of air. Any more charge leaks off in sparks


Figure P25.49 as shown in Figure P25.49. Assume the dome has a diameter of 30.0 cm and is surrounded by dry air with a "breakdown" electric field of $3.00 \times 10^{6} \mathrm{~V} / \mathrm{m}$. (a) What is the maximum potential of the dome? (b) What is the maximum charge on the dome?

## Additional Problems

50. Why is the following situation impossible? In the Bohr model of the hydrogen atom, an electron moves in a circular orbit about a proton. The model states that the electron can exist only in certain allowed orbits around the proton: those whose radius $r$ satisfies $r=n^{2}(0.0529 \mathrm{~nm})$, where $n=1,2$,
$3, \ldots$. For one of the possible allowed states of the atom, the electric potential energy of the system is -13.6 eV .
51. Review. From a large distance away, a particle of mass 2.00 g and charge $15.0 \mu \mathrm{C}$ is fired at $21.0 \hat{\mathbf{i}} \mathrm{~m} / \mathrm{s}$ straight toward a second particle, originally stationary but free to move, with mass 5.00 g and charge $8.50 \mu \mathrm{C}$. Both particles are constrained to move only along the $x$ axis. (a) At the instant of closest approach, both particles will be moving at the same velocity. Find this velocity. (b) Find the distance of closest approach. After the interaction, the particles will move far apart again. At this time, find the velocity of (c) the $2.00-\mathrm{g}$ particle and (d) the $5.00-\mathrm{g}$ particle.
52. S Review. From a large distance away, a particle of mass $m_{1}$ and positive charge $q_{1}$ is fired at speed $v$ in the positive $x$ direction straight toward a second particle, originally stationary but free to move, with mass $m_{2}$ and positive charge $q_{2}$. Both particles are constrained to move only along the $x$ axis. (a) At the instant of closest approach, both particles will be moving at the same velocity. Find this velocity. (b) Find the distance of closest approach. After the interaction, the particles will move far apart again. At this time, find the velocity of (c) the particle of mass $m_{1}$ and (d) the particle of mass $m_{2}$.
53. M The liquid-drop model of the atomic nucleus suggests high-energy oscillations of certain nuclei can split the nucleus into two unequal fragments plus a few neutrons. The fission products acquire kinetic energy from their mutual Coulomb repulsion. Assume the charge is distributed uniformly throughout the volume of each spherical fragment and, immediately before separating, each fragment is at rest and their surfaces are in contact. The electrons surrounding the nucleus can be ignored. Calculate the electric potential energy (in electron volts) of two spherical fragments from a uranium nucleus having the following charges and radii: $38 e$ and $5.50 \times 10^{-15} \mathrm{~m}$, and $54 e$ and $6.20 \times 10^{-15} \mathrm{~m}$.
54. Q|C Review. In fair weather, the electric field in the air at a particular location immediately above the Earth's surface is $120 \mathrm{~N} / \mathrm{C}$ directed downward. (a) What is the surface charge density on the ground? Is it positive or negative? (b) Imagine the surface charge density is uniform over the planet. What then is the charge of the whole surface of the Earth? (c) What is the Earth's electric potential due to this charge? (d) What is the difference in potential between the head and the feet of a person 1.75 m tall? (Ignore any charges in the atmosphere.) (e) Imagine the Moon, with $27.3 \%$ of the radius of the Earth, had a charge $27.3 \%$ as large, with the same sign. Find the electric force the Earth would then exert on the Moon. (f) State how the answer to part (e) compares with the gravitational force the Earth exerts on the Moon.
55. The electric potential immediately outside a charged conducting sphere is 200 V , and 10.0 cm farther from the center of the sphere the potential is 150 V . Determine (a) the radius of the sphere and (b) the charge on it. The electric potential immediately outside another charged conducting sphere is 210 V , and 10.0 cm farther from the center the magnitude of the electric field is $400 \mathrm{~V} / \mathrm{m}$. Determine (c) the radius of the sphere and (d) its charge on it. (e) Are the answers to parts (c) and (d) unique?
56. On a dry winter day, you scuff your leather-soled shoes across a carpet and get a shock when you extend the tip of one finger toward a metal doorknob. In a dark room, you see a spark perhaps 5 mm long. Make order-of-magnitude estimates of (a) your electric potential and (b) the charge on your body before you touch the doorknob. Explain your reasoning.
57. The electric potential everywhere on the $x y$ plane is

$$
V=\frac{36}{\sqrt{(x+1)^{2}+y^{2}}}-\frac{45}{\sqrt{x^{2}+(y-2)^{2}}}
$$

where $V$ is in volts and $x$ and $y$ are in meters. Determine the position and charge on each of the particles that create this potential.
58. $\mathbf{Q} \mid \mathbf{C} \mathbf{S}$ (a) Use the exact result from Example 25.4 to find the electric potential created by the dipole described in the example at the point $(3 a, 0)$. (b) Explain how this answer compares with the result of the approximate expression that is valid when $x$ is much greater than $a$.
59. Calculate the work that must be done on charges brought from infinity to charge a spherical shell of radius $R=$ 0.100 m to a total charge $Q=125 \mu \mathrm{C}$.
60. S Calculate the work that must be done on charges brought from infinity to charge a spherical shell of radius $R$ to a total charge $Q$.
S From Gauss's law, the electric field set up by a uniform line of charge is

$$
\overrightarrow{\mathbf{E}}=\left(\frac{\lambda}{2 \pi \epsilon_{0} r}\right) \hat{\mathbf{r}}
$$

where $\hat{\mathbf{r}}$ is a unit vector pointing radially away from the line and $\lambda$ is the linear charge density along the line. Derive an expression for the potential difference between $r=r_{1}$ and $r=r_{2}$.
62. Why is the following situation impossible? You set up an apparatus in your laboratory as follows. The $x$ axis is the symmetry axis of a stationary, uniformly charged ring of radius $R=0.500 \mathrm{~m}$ and charge $Q=50.0 \mu \mathrm{C}$ (Fig. P25.62). You place a particle with charge $Q=$


Figure P25.62 $50.0 \mu \mathrm{C}$ and mass $m=$ 0.100 kg at the center of the ring and arrange for it to be constrained to move only along the $x$ axis. When it is displaced slightly, the particle is repelled by the ring and accelerates along the $x$ axis. The particle moves faster than you expected and strikes the opposite wall of your laboratory at $40.0 \mathrm{~m} / \mathrm{s}$.
63. $\mathbf{S}$ The thin, uniformly charged rod shown in Figure P25.63 has a linear charge density $\lambda$. Find an expression for the electric potential at $P$.


Figure P25.63
64. Q|C A uniformly charged filament lies along the $x$ axis between $x=a=1.00 \mathrm{~m}$ and $x=a+\ell=3.00 \mathrm{~m}$ as shown in Figure P25.64. The total charge on the filament is 1.60 nC . Calculate successive approximations for the electric potential at the origin by modeling the filament as (a) a single charged particle at $x=2.00 \mathrm{~m}$, (b) two $0.800-\mathrm{nC}$ charged particles at $x=1.5 \mathrm{~m}$ and $x=2.5 \mathrm{~m}$, and (c) four $0.400-\mathrm{nC}$ charged particles at $x=1.25 \mathrm{~m}, x=1.75 \mathrm{~m}, x=2.25 \mathrm{~m}$, and $x=2.75 \mathrm{~m}$. (d) Explain how the results compare with the potential given by the exact expression

$$
V=\frac{k_{e} Q}{\ell} \ln \left(\frac{\ell+a}{a}\right)
$$



Figure P25.64
65. Review. Two parallel plates having charges of equal magnitude but opposite sign are separated by 12.0 cm . Each plate has a surface charge density of $36.0 \mathrm{nC} / \mathrm{m}^{2}$. A proton is released from rest at the positive plate. Determine (a) the magnitude of the electric field between the plates from the charge density, (b) the potential difference between the plates, (c) the kinetic energy of the proton when it reaches the negative plate, (d) the speed of the proton just before it strikes the negative plate, (e) the acceleration of the proton, and (f) the force on the proton. (g) From the force, find the magnitude of the electric field. (h) How does your value of the electric field compare with that found in part (a)?
66. S A Geiger-Mueller tube is a radiation detector that consists of a closed, hollow, metal cylinder (the cathode) of inner radius $r_{a}$ and a coaxial cylindrical wire (the anode) of radius $r_{b}$ (Fig. P25.66a). The charge per unit length on the anode is $\lambda$, and the charge per unit length on the cathode is $-\lambda$. A gas fills the space between the electrodes. When the tube is in use (Fig. P25.66b) and a high-energy elementary particle passes through this space, it can ionize an atom of the gas. The strong electric field makes the resulting ion and electron accelerate in opposite directions. They strike other molecules of the gas to ionize them, producing an avalanche of electrical discharge. The pulse of electric current between the wire and the cylinder is counted by an external circuit. (a) Show that the magnitude of the electric potential difference between the wire and the cylinder is

$$
\Delta V=2 k_{e} \lambda \ln \left(\frac{r_{a}}{r_{b}}\right)
$$

(b) Show that the magnitude of the electric field in the space between cathode and anode is

$$
E=\frac{\Delta V}{\ln \left(r_{a} / r_{b}\right)}\left(\frac{1}{r}\right)
$$

where $r$ is the distance from the axis of the anode to the point where the field is to be calculated.


Figure P25.66
67. S When an uncharged conducting sphere of radius $a$ is placed at the origin of an $x y z$ coordinate system that lies in an initially uniform electric field $\overrightarrow{\mathbf{E}}=E_{0} \hat{\mathbf{k}}$, the resulting electric potential is $V(x, y, z)=V_{0}$ for points inside the sphere and

$$
V(x, y, z)=V_{0}-E_{0} z+\frac{E_{0} a^{3} z}{\left(x^{2}+y^{2}+z^{2}\right)^{3 / 2}}
$$

for points outside the sphere, where $V_{0}$ is the (constant) electric potential on the conductor. Use this equation to determine the $x, y$, and $z$ components of the resulting electric field (a) inside the sphere and (b) outside the sphere.

## Challenge Problems

68. S A particle with charge $q$ is located at $x=-R$, and a particle with charge $-2 q$ is located at the origin. Prove that the equipotential surface that has zero potential is a sphere centered at $(-4 R / 3,0,0)$ and having a radius $r=\frac{2}{3} R$.
69. S (a) A uniformly charged cylindrical shell with no end caps has total charge $Q$, radius $R$, and length $h$. Determine the electric potential at a point a distance $d$ from the right end of the cylinder as shown in Figure P25.69. Suggestion: Use the result of Example 25.5 by treating the cylinder as a collection of ring charges. (b) What If? Use the result of Example 25.6 to solve the same problem for a solid cylinder.


Figure P25.69
70. S As shown in Figure P25.70, two large, parallel, vertical conducting plates separated by distance $d$ are charged so that their potentials are $+V_{0}$ and $-V_{0}$. A small conducting ball of mass $m$ and radius $R$ (where $R \ll$ d) hangs midway between the plates. The thread of length $L$ supporting the ball is a conducting wire connected to ground, so


Figure P25.70
the potential of the ball is fixed at $V=0$. The ball hangs straight down in stable equilibrium when $V_{0}$ is sufficiently small. Show that the equilibrium of the ball is unstable if $V_{0}$ exceeds the critical value $k_{e} d^{2} m g /(4 R L)$. Suggestion: Consider the forces on the ball when it is displaced a distance $x \ll L$.
71. S An electric dipole is located along the $y$ axis as shown in Figure P25.71. The magnitude of its electric dipole moment is defined as $p=2 a q$. (a) At a point $P$, which is far from the dipole $(r \gg a)$, show that the electric potential is

$$
V=\frac{k_{e} p \cos \theta}{r^{2}}
$$

(b) Calculate the radial component $E_{r}$ and the perpendicular component $E_{\theta}$ of the associated


Figure P25.71 electric field. Note that $E_{\theta}=-(1 / r)(\partial V / \partial \theta)$. Do these results seem reasonable for (c) $\theta=90^{\circ}$ and $0^{\circ}$ ? (d) For $r=0$ ? (e) For the dipole arrangement shown in Figure P25.71, express $V$ in terms of Cartesian coordinates using $r=\left(x^{2}+y^{2}\right)^{1 / 2}$ and

$$
\cos \theta=\frac{y}{\left(x^{2}+y^{2}\right)^{1 / 2}}
$$

(f) Using these results and again taking $r \gg a$, calculate the field components $E_{x}$ and $E_{y}$.
72. S A solid sphere of radius $R$ has a uniform charge density $\rho$ and total charge $Q$. Derive an expression for its total electric potential energy. Suggestion: Imagine the sphere is constructed by adding successive layers of concentric shells of charge $d q=\left(4 \pi r^{2} d r\right) \rho$ and use $d U=V d q$.
73. S A disk of radius $R$ (Fig. P25.73) has a nonuniform surface charge density $\sigma=$ $C r$, where $C$ is a constant and $r$ is measured from the center of the disk to a point on the surface of the disk. Find (by direct integration) the electric potential at $P$.


Figure P25.73
74. S Four balls, each with mass $m$, are connected by four nonconducting strings to form a square with side $a$ as shown in Figure P25.74. The assembly is placed on a nonconducting, frictionless, horizontal surface. Balls 1 and 2 each have charge $q$, and balls 3 and 4


Figure P25.74 are uncharged. After the string connecting balls 1 and 2 is cut, what is the maximum speed of balls 3 and 4?

