Electric Potential Energy  The change $\Delta U$ in the electric potential energy $U$ of a point charge as the charge moves from an initial point $i$ to a final point $f$ in an electric field is

$$\Delta U = U_f - U_i = -W,$$

where $W$ is the work done by the electrostatic force (due to the external electric field) on the point charge during the move from $i$ to $f$. If the potential energy is defined to be zero at infinity, the electric potential energy $U$ of the point charge at a particular point is

$$U = -W_e.$$  \hspace{1cm} (24-2)

Here $W_e$ is the work done by the electrostatic force on the point charge as the charge moves from infinity to the particular point.

Electric Potential Difference and Electric Potential  We define the potential difference $\Delta V$ between two points $i$ and $f$ in an electric field as

$$\Delta V = V_f - V_i = -\frac{W}{q},$$

where $q$ is the charge of a particle on which work $W$ is done by the electric field as the particle moves from point $i$ to point $f$. The potential at a point is defined as

$$V = -\frac{W_e}{q}.$$  \hspace{1cm} (24-8)

Here $W_e$ is the work done on the particle by the electric field as the particle moves in from infinity to the point. The SI unit of potential is the volt: 1 volt = 1 joule per coulomb.

Potential and potential difference can also be written in terms of the electric potential energy $U$ of a particle of charge $q$ in an electric field:

$$V = \frac{U}{q},$$

$$\Delta V = V_f - V_i = \frac{U_f}{q} - \frac{U_i}{q} = \frac{\Delta U}{q}.$$  \hspace{1cm} (24-6)

Equipotential Surfaces  The points on an equipotential surface all have the same electric potential. The work done on a test charge in moving it from one such surface to another is independent of the locations of the initial and final points on these surfaces and of the path that joins the points. The electric field $\vec{E}$ is always directed perpendicularly to corresponding equipotential surfaces.

Finding $V$ from $\vec{E}$  The electric potential difference between two points $i$ and $f$ is

$$V_f - V_i = -\int_i^f \vec{E} \cdot d\vec{s},$$

where the integral is taken over any path connecting the points. If the integration is difficult along any particular path, we can choose a different path along which the integration might be easier. If we choose $V_i = 0$, we have, for the potential at a particular point,

$$V = -\int_i^f \vec{E} \cdot d\vec{s}.$$  \hspace{1cm} (24-19)

Potential Due to Point Charges  The electric potential due to a single point charge at a distance $r$ from that point charge is

$$V = \frac{1}{4\pi\varepsilon_0} \frac{q}{r},$$

where $V$ has the same sign as $q$. The potential due to a collection of point charges is

$$V = \sum_{i=1}^{n} \frac{q_i}{r_i}.$$  \hspace{1cm} (24-27)

Potential Due to an Electric Dipole  At a distance $r$ from an electric dipole with dipole moment magnitude $p = qd$, the electric potential of the dipole is

$$V = \frac{1}{4\pi\varepsilon_0} \frac{p \cos \theta}{r^2},$$

for $r \gg d$; the angle $\theta$ is defined in Fig. 24-10.

Potential Due to a Continuous Charge Distribution  For a continuous distribution of charge, Eq. 24-27 becomes

$$V = \frac{1}{4\pi\varepsilon_0} \int \frac{dq}{r},$$

in which the integral is taken over the entire distribution.

Calculating $\vec{E}$ from $V$  The component of $\vec{E}$ in any direction is the negative of the rate at which the potential changes with distance in that direction:

$$E_s = -\frac{\delta V}{\delta s}.$$  \hspace{1cm} (24-40)

The $x$, $y$, and $z$ components of $\vec{E}$ may be found from

$$E_x = -\frac{\delta V}{\delta x}; \quad E_y = -\frac{\delta V}{\delta y}; \quad E_z = -\frac{\delta V}{\delta z}.$$  \hspace{1cm} (24-41)

When $\vec{E}$ is uniform, Eq. 24-40 reduces to

$$E = -\frac{\Delta V}{\Delta s},$$

where $s$ is perpendicular to the equipotential surfaces. The electric field is zero parallel to an equipotential surface.

Electric Potential Energy of a System of Point Charges  The electric potential energy of a system of point charges is equal to the work needed to assemble the system with the charges initially at rest and infinitely distant from each other. For two charges at separation $r$,

$$U = W = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r}.$$  \hspace{1cm} (24-43)

Potential of a Charged Conductor  An excess charge placed on a conductor will, in the equilibrium state, be located entirely on the outer surface of the conductor. The charge will distribute itself so that the following occur: (1) The entire conductor, including interior points, is at a uniform potential. (2) At every internal point, the electric field due to the charge cancels the external electric field that otherwise would have been there. (3) The net electric field at every point on the surface is perpendicular to the surface.
** View All Solutions Here **

**QUESTIONS**

1. In Fig. 24-21, eight particles form a square, with distance $d$ between adjacent particles. What is the electric potential at point $P$ at the center of the square if the electric potential is zero at infinity?

2. Figure 24-22 shows three sets of cross sections of equipotential surfaces; all three cover the same size region of space. (a) Rank the arrangements according to the magnitude of the electric field present in the region, greatest first. (b) In which is the electric field directed down the page?

3. Figure 24-23 shows four pairs of charged particles. For each pair, let $V = 0$ at infinity and consider $V_{net}$ at points on the $x$ axis. For which pairs is there a point at which $V_{net} = 0$? (a) between the particles and (b) to the right of the particles? (c) At such a point is $E_{net}$ due to the particles equal to zero? (d) For each pair, are there off-axis points (other than at infinity) where $V_{net} = 0$?

4. Figure 24-24 gives the electric potential $V$ as a function of $x$. (a) Rank the five regions according to the magnitude of the electric field within them, greatest first. What is the direction of the field along the $x$ axis in (b) region 2 and (c) region 4?

5. Figure 24-25 shows three paths along which we can move the positively charged sphere $A$ closer to positively charged sphere $B$, which is held fixed in place. (a) Would sphere $A$ be moved to a higher or lower electric potential? Is the work done (b) by our force and (c) by the electric field due to $B$ positive, negative, or zero? (d) Rank the paths according to the work our force does, greatest first.

6. Figure 24-26 shows four arrangements of charged particles, all the same distance from the origin. Rank the situations according to the net electric potential at the origin, most positive first. Take the potential to be zero at infinity.

7. Figure 24-27 shows a system of three charged particles. If you move the particle of charge $+q$ from point $A$ to point $D$, are the following quantities positive, negative, or zero: (a) the change in the electric potential energy of the three-particle system, (b) the work done by the net electrostatic force on the particle you moved (that is, the net force due to the other two particles), and (c) the work done by your force? (d) What are the answers to (a) through (c) if, instead, the particle is moved from $B$ to $C$?

8. In the situation of Question 7, is the work done by your force positive, negative, or zero if the particle is moved (a) from $A$ to $B$, (b) from $A$ to $C$, and (c) from $B$ to $D$? (d) Rank those moves according to the magnitude of the work done by your force, greatest first.

9. Figure 24-28 shows four arrangements of charged particles with identical separations. (a) Rank the pairs according to their electric potential energy (that is, the energy of the two-particle system), greatest (most positive) first. (b) For each pair, if the separation between the particles is increased, does the potential energy of the pair increase or decrease?

10. (a) In Fig. 24-28a, what is the potential at point $P$ due to charge $Q$ at distance $R$ from $P$? Set $V = 0$ at infinity. (b) In Fig. 24-28b, the same charge $Q$ has been spread uniformly over a circular arc of radius $R$ and central angle $40^\circ$. What is the potential at point $P$, the center of curvature of the arc? (c) In Fig. 24-28c, the same charge $Q$ has been spread uniformly over a circle of radius $R$. What is the potential at point $P$, the center of the circle? (d) Rank the three situations according to the magnitude of the electric field that is set up at $P$, greatest first.
** View All Solutions Here **

CHAPTER 24 ELECTRIC POTENTIAL

sec. 24-3 Electric Potential

1. SSM A particular 12 V car battery can send a total charge of 84 A·h (ampere-hours) through a circuit, from one terminal to the other. (a) How many coulombs of charge does this represent? (Hint: See Eq. 21-3.) (b) If this entire charge undergoes a change in electric potential of 12 V, how much energy is involved?

2. The electric potential difference between the ground and a cloud in a particular thunderstorm is 1.2 × 10^9 V. In the unit electron-volts, what is the magnitude of the change in the electric potential energy of an electron that moves between the ground and the cloud?

3. Much of the material making up Saturn’s rings is in the form of tiny dust grains having radii on the order of 10^-6 m. These grains are located in a region containing a dilute ionized gas, and they pick up excess electrons. As an approximation, suppose each grain is placed anywhere between the two plates. (Neglect fringing.) (a) Find the electric field at the position of the electron. (b) What is the potential difference between the plates?

5. SSM An infinite nonconducting sheet has a surface charge density \( \sigma = 0.10 \) \( \mu \)C/m² on one side. How far apart are equipotential surfaces whose potentials differ by 50 V?

6. When an electron moves from A to B along an electric field line in Fig. 24-29, the electric field does 3.94 × 10^-19 J of work on it. What are the electric potential differences (a) \( V_B - V_A \), (b) \( V_C - V_A \), and (c) \( V_C - V_B \)?

7. The electric field in a region of space has the components \( E_x = E_y = 0 \) and \( E_z = (4.00 \text{ N/C})z \). Point A is on the y axis at \( y = 3.00 \) m, and point B is on the x axis at \( x = 4.00 \) m. What is the potential difference \( V_B - V_A \)?

8. A graph of the x component of the electric field as a function of x in a region of space is shown in Fig. 24-30. The scale of the vertical axis is set by \( E_x = 20.0 \text{ N/C} \). The y and z components of the electric field are zero in this region. If the electric potential at the origin is 10 V, (a) what is the electric potential at \( x = 2.0 \) m, (b) what is the greatest positive value of the electric potential for points on the x axis for which \( 0 \leq x \leq 6.0 \) m, and (c) for what value of x is the electric potential zero?

9. An infinite nonconducting sheet has a surface charge density \( \sigma = +5.80 \text{ pC/m}^2 \). (a) How much work is done by the electric field due to the sheet if a particle of charge \( q = +1.60 \times 10^{-19} \text{ C} \) is moved from the sheet to a point \( P \) at distance \( d = 3.56 \text{ cm} \) from the sheet? (b) If the electric potential \( V \) is defined to be zero on the sheet, what is \( V \) at \( P \)?

10. Two uniformly charged, infinite, nonconducting planes are parallel to a yz plane and positioned at \( x = 50 \) cm and \( x = +50 \) cm. The charge densities on the planes are \( -50 \mu \text{C/m}^2 \) and \( +25 \text{nC/m}^2 \), respectively. What is the magnitude of the potential difference between the origin and the point on the x axis at \( x = +80 \) cm? (Hint: Use Gauss’ law.)

11. A nonconducting sphere has radius \( R = 2.31 \text{ cm} \) and uniformly distributed charge \( q = +3.50 \text{ fC} \). Take the electric potential at the sphere’s center to be \( V_0 = 0 \). What is \( V \) at radial distance (a) \( r = 1.45 \text{ cm} \) and (b) \( r = R \)? (Hint: See Section 23-9.)

sec. 24-7 Potential Due to a Group of Point Charges

12. As a space shuttle moves through the dilute ionized gas of Earth’s ionosphere, the shuttle’s potential is typically changed by \(-1.0 \) V during one revolution. Assuming the shuttle is a sphere of radius 10 m, estimate the amount of charge it collects.

13. What are (a) the charge and (b) the charge density on the surface of a conducting sphere of radius 0.15 m whose potential is 200 V (with \( V = 0 \) at infinity)?

14. Consider a point charge \( q = 1.0 \mu \text{C} \), point \( A \) at distance \( d_1 = 2.0 \text{ m} \) from \( q \), and point \( B \) at distance \( d_2 = 1.0 \text{ m} \). (a) If \( A \) and \( B \) are diametrically opposite each other, as in Fig. 24-31a, what is the elec-

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tric potential difference $V_A - V_B$? (b) What is the electric potential difference if $A$ and $B$ are located as in Fig. 24-31b?


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**CHAPTER 24 ELECTRIC POTENTIAL**

24. In Fig. 24-38, a plastic rod having a uniformly distributed charge \( Q = -25.6 \, \text{pC} \) has been bent into a circular arc of radius \( R = 3.71 \, \text{cm} \) and central angle \( \phi = 120° \). With \( V = 0 \) at infinity, what is the electric potential at \( P \), the center of curvature of the rod?

25. A plastic rod has been bent into a circle of radius \( R = 8.20 \, \text{cm} \). It has a charge \( Q_1 = +4.20 \, \text{pC} \) uniformly distributed along one-quarter of its circumference and a charge \( Q_2 = -6Q_1 \) uniformly distributed along the rest of the circumference (Fig. 24-39). With \( V = 0 \) at infinity, what is the electric potential at (a) the center \( C \) of the circle and (b) point \( P \), on the central axis of the circle at distance \( D = 6.71 \, \text{cm} \) from the center?

26. Figure 24-40 shows a thin rod with a uniform charge density of 2.00 \( \mu \text{C/m} \). Evaluate the electric potential at point \( P \) if \( d = D = L/4.00 \).

27. In Fig. 24-41, three thin plastic rods form quarter-circles with a common center of curvature at the origin. The uniform charges on the rods are \( Q_1 = +30 \, \text{nC} \), \( Q_2 = +3.0Q_1 \), and \( Q_3 = -8.0Q_1 \). What is the net electric potential at the origin due to the rods?

28. Figure 24-42 shows a thin plastic rod of length \( L = 12.0 \, \text{cm} \) and uniform positive charge \( Q = 56.1 \, \text{fC} \) lying on an \( x \)-axis. With \( V = 0 \) at infinity, find the electric potential at point \( P_1 \) on the axis, at distance \( d = 2.50 \, \text{cm} \) from one end of the rod.

29. In Fig. 24-43, what is the net electric potential at the origin due to the circular arc of charge \( Q_1 = +7.21 \, \text{pC} \) and the two particles of charges \( Q_2 = 4.00Q_1 \) and \( Q_3 = -2.00Q_1 \)? The arc’s center of curvature is at the origin and its radius is \( R = 2.00 \, \text{m} \); the angle indicated is \( \theta = 20.0° \).

30. The smiling face of Fig. 24-44 consists of three items:
1. a thin rod of charge \(-3.0 \, \mu \text{C} \) that forms a full circle of radius 6.0 cm;
2. a second thin rod of charge \(2.0 \, \mu \text{C} \) that forms a circular arc of radius 4.0 cm, subtending an angle of 90° about the center of the full circle;
3. an electric dipole with a dipole moment that is perpendicular to a radial line and has magnitude \(1.28 \times 10^{-22} \, \text{C} \cdot \text{m} \).

What is the net electric potential at the center?

31 SSM WWW A plastic disk of radius \( R = 64.0 \, \text{cm} \) is charged on one side with a uniform surface charge density \( \sigma = 7.73 \, \text{C/m}^2 \), and then three quadrants of the disk are removed. The remaining quadrant is shown in Fig. 24-45. With \( V = 0 \) at infinity, what is the potential due to the remaining quadrant at point \( P \), which is on the central axis of the original disk at distance \( D = 25.9 \, \text{cm} \) from the original center?

32 A nonuniform linear charge distribution given by \( \lambda = bx \), where \( b \) is a constant, is located along an \( x \)-axis from \( x = 0 \) to \( x = 0.20 \, \text{m} \). If \( b = 20 \, \text{nC/m} \) and \( V = 0 \) at infinity, what is the electric potential at (a) the origin and (b) the point \( y = 0.15 \, \text{m} \) on the \( y \)-axis?

33 The thin plastic rod shown in Fig. 24-42 has length \( L = 12.0 \, \text{cm} \) and a nonuniform linear charge density \( \lambda = cx \), where \( c = 28.9 \)
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sec. 24-10 Calculating the Field from the Potential

•42 (a) What is the electric potential energy of two electrons separated by 2.00 nm? (b) If the separation increases, does the potential energy increase or decrease?

•43 SSM ILW WWW How much work is required to set up the arrangement of Fig. 24-47 if \( q = 2.30 \) pC, \( a = 64.0 \) cm, and the particles are initially infinitely far apart and at rest?

•44 In Fig. 24-48, seven charged particles are fixed in place to form a square with an edge length of 4.0 cm. How much work must we do to bring a particle of charge +6e initially at rest from an infinite distance to the center of the square?

Fig. 24-47 Problem 43.

Fig. 24-48 Problem 44.

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pC/m². With \( V = 0 \) at infinity, find the electric potential at point \( P_1 \) on the axis, at distance \( d = 3.00 \) cm from one end.

sec. 24-10 Calculating the Field from the Potential

•34 Two large parallel metal plates are 1.5 cm apart and have charges of equal magnitudes but opposite signs on their facing surfaces. Take the potential of the negative plate to be zero. If the potential halfway between the plates is then +5.0 V, what is the electric field in the region between the plates?

•35 The electric potential at points in an \( xy \) plane is given by \( V = (2.0 \text{ V/m²})x^2 - (3.0 \text{ V/m²})y^2 \). In unit-vector notation, what is the electric field at the point (3.0 m, 2.0 m)?

•36 The electric potential \( V \) in the space between two flat parallel plates 1 and 2 is given (in volts) by \( V = 1500x^2 \), where \( x \) (in meters) is the perpendicular distance from plate 1. At \( x = 1.3 \) cm, (a) what is the magnitude of the electric field and (b) is the field directed toward or away from plate 1?

•37 SSM What is the magnitude of the electric field at the point (3.00 - 2.00j + 4.00k) m if the electric potential is given by \( V = 2.00x^2yz^3 \), where \( V \) is in volts and \( x, y, \) and \( z \) are in meters?

•38 Figure 24-42 shows a thin plastic rod of length \( L = 13.5 \) cm and uniform charge 43.6 FC. (a) In terms of distance \( d \), find an expression for the electric potential at point \( P_1 \). (b) Next, substitute variable \( x \) for \( d \) and find an expression for the magnitude of the component \( E_x \) of the electric field at \( P_1 \). (c) What is the direction of \( E_x \), relative to the positive direction of the \( x \) axis? (d) What is the value of \( E_x \) at \( P_1 \) for \( x = d = 6.20 \) cm? (e) From the symmetry in Fig. 24-42, determine \( E_y \) at \( P_1 \).

•39 An electron is placed in an \( xy \) plane where the electric potential depends on \( x \) and \( y \) as shown in Fig. 24-46 (the potential does not depend on \( z \)). The scale of the vertical axis is set by \( V_y = 500 \) V. In unit-vector notation, what is the electric force on the electron?

Fig. 24-46 Problem 39.

•40 The thin plastic rod of length \( L = 10.0 \) cm in Fig. 24-42 has a nonuniform linear charge density \( \lambda = cx \), where \( c = 49.9 \) pC/m². (a) With \( V = 0 \) at infinity, find the electric potential at point \( P_1 \) on the \( y \) axis at \( y = D = 3.56 \) cm. (b) Find the electric field component \( E_y \) at \( P_2 \). (c) Why cannot the field component \( E_x \) at \( P_2 \) be found using the result of (a)?

sec. 24-11 Electric Potential Energy of a System of Point Charges

•41 A particle of charge +7.5 \( \mu \)C is released from rest at the point \( x = 60 \) cm on an \( x \) axis. The particle begins to move due to the presence of a charge \( Q \) that remains fixed at the origin. What is the kinetic energy of the particle at the instant it has moved 40 cm if (a) \( Q = +20 \) \( \mu \)C and (b) \( Q = -20 \) \( \mu \)C?

•42 (a) What is the electric potential energy of two electrons separated by 2.00 nm? (b) If the separation increases, does the potential energy increase or decrease?

•43 SSM ILW WWW How much work is required to set up the arrangement of Fig. 24-47 if \( q = 2.30 \) pC, \( a = 64.0 \) cm, and the particles are initially infinitely far apart and at rest?

•44 In Fig. 24-48, seven charged particles are fixed in place to form a square with an edge length of 4.0 cm. How much work must we do to bring a particle of charge +6e initially at rest from an infinite distance to the center of the square?

Fig. 24-47 Problem 43.

Fig. 24-48 Problem 44.

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the indicated point near two fixed particles of charges \( q_1 = +4e \) and \( q_2 = -q_1/2 \). Distance \( d = 1.40 \text{ cm} \), \( \theta_1 = 43^\circ \), and \( \theta_2 = 60^\circ \).

51 In the rectangle of Fig. 24-50, the sides have lengths 5.0 cm and 15 cm. \( q_1 = -5.0 \mu C \) and \( q_2 = +2.0 \mu C \). With \( V = 0 \) at infinity, what is the electric potential at (a) corner \( A \) and (b) corner \( B \)? (c) How much work is required to move a charge \( q_3 = +3.0 \mu C \) from \( B \) to \( A \) along a diagonal of the rectangle? (d) Does this work increase or decrease the electric potential energy of the three-charge system? Is more, less, or the same work required if \( q_3 \) is moved along a path that is (e) inside the rectangle but not on a diagonal and (f) outside the rectangle?

52 Figure 24-51a shows an electron moving along an electric dipole axis toward the negative side of the dipole. The dipole is fixed in place. The electron was initially very far from the dipole, with kinetic energy 100 eV. Figure 24-51b gives the kinetic energy \( K \) of the electron versus its distance \( r \) from the dipole center. The scale of the horizontal axis is set by \( r_i = 0.10 \text{ m} \). What is the magnitude of the dipole moment?

53 Two tiny metal spheres \( A \) and \( B \), mass \( m_A = 5.00 \text{ g} \) and \( m_B = 10.0 \text{ g} \), have equal positive charge \( q = 5.00 \mu C \). The spheres are connected by a massless nonconducting string of length \( d = 1.00 \text{ m} \), which is much greater than the radii of the spheres. (a) What is the electric potential energy of the system? (b) Suppose you cut the string. At that instant, what is the acceleration of each sphere? (c) A long time after you cut the string, what is the speed of each sphere?

54 A positron (charge \( +e \), mass equal to the electron mass) is moving at \( 1.0 \times 10^7 \text{ m/s} \) in the positive direction of an \( x \) axis when, at \( x = 0 \), it encounters an electric field directed along the \( x \) axis. The electric potential \( V \) associated with the field is given in Fig. 24-52. The scale of the vertical axis is set by \( V_s = 500.0 \text{ V} \). (a) Does the positron emerge from the field at \( x = 0 \) (which means its motion is reversed) or at \( x = 0.50 \text{ m} \) (which means its motion is not reversed)? (b) What is its speed when it emerges?

55 An electron is projected with an initial speed of \( 3.2 \times 10^7 \text{ m/s} \) directly toward a proton that is fixed in place. If the electron is initially a great distance from the proton, at what distance from the proton is the speed of the electron instantaneously equal to twice the initial value?

56 Figure 24-53a shows three particles on an \( x \) axis. Particle 1 (with a charge of \( +5.0 \mu C \)) and particle 2 (with a charge of \( +3.0 \mu C \)) are fixed in place with separation \( d = 4.0 \text{ cm} \). Particle 3 can be moved along the \( x \) axis to the right of particle 2. Figure 24-53b gives the electric potential energy \( U \) of the three-particle system as a function of the \( x \) coordinate of particle 3. The scale of the vertical axis is set by \( U_s = 5.0 \text{ J} \). What is the charge of particle 3?

57 SSM Identical \( 50 \mu C \) charges are fixed on an \( x \) axis at \( x = \pm 3.0 \text{ m} \). A particle of charge \( q = -15 \mu C \) is then released from rest at a point on the positive part of the \( y \) axis. Due to the symmetry of the situation, the particle moves along the \( y \) axis and has kinetic energy 1.2 J as it passes through the point \( x = 0, y = 4.0 \text{ m} \). (a) What is the kinetic energy of the particle as it passes through the origin? (b) At what negative value of \( y \) will the particle momentarily stop?

58 Proton in a well. Figure 24-54 shows electric potential \( V \) along an \( x \) axis. The scale of the vertical axis is set by \( V_s = 10.0 \text{ V} \). A proton is to be released at \( x = 3.5 \text{ cm} \) with initial kinetic energy 4.00 eV. (a) If it is initially moving in the negative direction of the axis, does it reach a turning point (if so, what is the \( x \) coordinate of that point) or does it escape from the plotted region (if so, what is its speed at \( x = 0 \)?) (b) If it is initially moving in the positive direction of the axis, does it reach a turning point (if so, what is the \( x \) coordinate of that point) or does it escape from the plotted region (if so, what is its speed at \( x = 6.0 \text{ cm} \)?) What are the (c) magnitude \( F \) and (d) direction (positive or negative direction of the \( x \) axis) of the electric force on the proton if the proton moves just to the left of \( x = 3.0 \text{ cm} \)?

59 In Fig. 24-55, a charged particle (either an electron or a proton) is moving rightward between two parallel charged plates separated by distance \( d = 2.00 \text{ mm} \). The plate potentials are \( V_1 = -70.0 \text{ V} \) and \( V_2 = -50.0 \text{ V} \). The particle is slowing from an initial
speed of 90.0 km/s at the left plate. (a) Is the particle an electron or a proton? (b) What is its speed just as it reaches plate 2?

**60** In Fig. 24-56a, we move an electron from an infinite distance to a point at distance \( R = 8.00 \text{ cm} \) from a tiny charged ball. The move requires work \( W = 2.16 \times 10^{-13} \text{ J} \) by us. (a) What is the charge \( Q \) on the ball? In Fig. 24-56b, the ball has been sliced up and the slices spread out so that an equal amount of charge is at the hour positions on a circular clock face of radius \( R = 8.00 \text{ cm} \). Now the electron is brought from an infinite distance to the center of the circle. (b) With that addition of the electron to the system of 12 charged particles, what is the change in the electric potential energy of the system?

![Fig. 24-56 Problem 60.](image)

**61** Suppose \( N \) electrons can be placed in either of two configurations. In configuration 1, they are all placed on the circumference of a narrow ring of radius \( R \) and are uniformly distributed so that the distance between adjacent electrons is the same everywhere. In configuration 2, \( N - 1 \) electrons are uniformly distributed on the ring and one electron is placed in the center of the ring. (a) What is the smallest value of \( N \) for which the second configuration is less energetic than the first? (b) For that value of \( N \), consider any one configuration electron — call it \( e_0 \). How many other circumference electrons are closer to \( e_0 \) than the central electron is?

**24-12 Potential of a Charged Isolated Conductor**

**62** Sphere 1 with radius \( R_1 \) has positive charge \( q \). Sphere 2 with radius \( 2.00 R_1 \) is far from sphere 1 and initially uncharged. After the separated spheres are connected with a wire thin enough to retain only negligible charge, (a) is potential \( V_1 \) of sphere 1 greater than, less than, or equal to potential \( V_2 \) of sphere 2? What fraction of \( q \) ends up on (b) sphere 1 and (c) sphere 2? (d) What is the ratio \( \sigma_1/\sigma_2 \) of the surface charge densities of the spheres?

**63** **SSM** **WWW** Two metal spheres, each of radius 3.0 cm, have a center-to-center separation of 2.0 m. Sphere 1 has charge \( +1.0 \times 10^{-8} \text{ C} \); sphere 2 has charge \( -3.0 \times 10^{-8} \text{ C} \). Assume that the separation is large enough for us to say that the charge on each sphere is uniformly distributed (the spheres do not affect each other). With \( V = 0 \) at infinity, calculate (a) the potential at the point halfway between the centers and the potential on the surface of (b) sphere 1 and (c) sphere 2.

**64** A hollow metal sphere has a potential of +400 V with respect to ground (defined to be at \( V = 0 \)) and a charge of \( 5.0 \times 10^{-7} \text{ C} \). Find the electric potential at the center of the sphere.

**65** **SSM** What is the excess charge on a conducting sphere of radius \( r = 0.15 \text{ m} \) if the potential of the sphere is 1500 V and \( V = 0 \) at infinity?

**66** Two isolated, concentric, conducting spherical shells have radii \( R_1 = 0.500 \text{ m} \) and \( R_2 = 1.00 \text{ m} \). Uniform charges \( q_1 = +2.00 \mu \text{C} \) and \( q_2 = +1.00 \mu \text{C} \), and negligible thicknesses. What is the magnitude of the electric field \( E \) at radial distance (a) \( r = 4.00 \text{ m} \), (b) \( r = 0.700 \text{ m} \), and (c) \( r = 2.00 \text{ m} \)? With \( V = 0 \) at infinity, what is \( V \) at (d) \( r = 4.00 \text{ m} \), (e) \( r = 1.00 \text{ m} \), (f) \( r = 0.700 \text{ m} \), (g) \( r = 0.500 \text{ m} \), (h) \( r = 0.200 \text{ m} \), and (i) \( r = 0 \) ? (j) Sketch \( E(r) \) and \( V(r) \).

**67** A metal sphere of radius 15 cm has a net charge of \( 3.0 \times 10^{-8} \text{ C} \). (a) What is the electric field at the sphere’s surface? (b) If \( V = 0 \) at infinity, what is the electric potential at the sphere’s surface? (c) At what distance from the sphere’s surface has the electric potential decreased by 500 V?

**Additional Problems**

**68** Here are the charges and coordinates of two point charges located in an \( xy \) plane: \( q_1 = +3.00 \times 10^{-8} \text{ C}, x = +3.50 \text{ cm}, y = +0.500 \text{ cm} \) and \( q_2 = -4.00 \times 10^{-8} \text{ C}, x = -2.00 \text{ cm}, y = +1.50 \text{ cm} \). How much work must be done to locate these charges at their given positions, starting from infinite separation?

**69** **SSM** A long, solid, conducting cylinder has a radius of 2.0 cm. The electric field at the surface of the cylinder is 160 N/C, directed radially outward. Let \( A, B, \) and \( C \) be points that are 1.0 cm, 2.0 cm, and 5.0 cm, respectively, from the central axis of the cylinder. What are (a) the magnitude of the electric field at \( C \) and the electric potential differences (b) \( V_A - V_B \), and (c) \( V_A - V_C \)?

**70** **The chocolate crumb mystery.** This story begins with Problem 60 in Chapter 23. (a) From the answer to part (a) of that problem, find an expression for the electric potential as a function of the radial distance \( r \) from the center of the pipe. (The electric potential is zero on the grounded pipe wall.) (b) For the typical volume charge density \( \rho = -1.1 \times 10^{-3} \text{ C/m}^3 \), what is the difference in the electric potential between the pipe’s center and its inside wall? (The story continues with Problem 60 in Chapter 25.)

**71** **SSM** Starting from Eq. 24-30, derive an expression for the electric field due to a dipole at a point on the dipole axis.

**72** The magnitude \( E \) of an electric field depends on the radial distance \( r \) according to \( E = Ar^4 \), where \( A \) is a constant with the unit volt–cubic meter. As a multiple of \( A \), what is the magnitude of the electric potential difference between \( r = 2.00 \text{ m} \) and \( r = 3.00 \text{ m} \)?

**73** (a) If an isolated conducting sphere 10 cm in radius has a net charge of \( 4.0 \mu \text{C} \) and if \( V = 0 \) at infinity, what is the potential on the surface of the sphere? (b) Can this situation actually occur, given that the air around the sphere undergoes electrical breakdown when the field exceeds 3.0 MV/m?

**74** Three particles, charge \( q_1 = +10 \mu \text{C} \), \( q_2 = -20 \mu \text{C} \), and \( q_3 = +30 \mu \text{C} \), are positioned at the vertices of an isosceles triangle as shown in Fig. 24-57. If \( a = 10 \text{ cm} \) and \( b = 6.0 \text{ cm} \), how much work must an external agent do to exchange the positions of (a) \( q_1 \) and \( q_2 \) and, instead, (b) \( q_1 \) and \( q_3 \)?

**75** An electric field of approximately 100 V/m is often observed near the surface of Earth. If this were the field over the entire
surface, what would be the electric potential of a point on the surface? (Set $V = 0$ at infinity.)

** Problem 76 **
A Gaussian sphere of radius 4.00 cm is centered on a ball that has a radius of 1.00 cm and a uniform charge distribution. The total (net) electric flux through the surface of the Gaussian sphere is $+5.60 \times 10^4 \text{ N} \cdot \text{m}^2/\text{C}$. What is the electric potential 12.0 cm from the center of the ball?

** Problem 77 **
In a Millikan oil-drop experiment (Section 22-8), a uniform electric field of $1.92 \times 10^3 \text{ N/C}$ is maintained in the region between two plates separated by 1.50 cm. Find the potential difference between the plates.

** Problem 78 **
Figure 24-58 shows three circular, nonconducting arcs of radius $R = 8.50 \text{ cm}$. The charges on the arcs are $q_1 = 4.52 \text{ pC}$, $q_2 = -2.00 \text{ pC}$, $q_3 = +3.00 \text{ pC}$. With $V = 0$ at infinity, what is the net electric potential of the arcs at the common center of curvature?

![Fig. 24-58](image)

** Problem 79 **
An electron is released from rest on the axis of an electric dipole that has charge $e$ and charge separation $d = 20 \text{ pm}$ and that is fixed in place. The release point is on the positive side of the dipole, at distance $7.0d$ from the dipole center. What is the electron's speed when it reaches a point $5.0d$ from the dipole center?

** Problem 80 **
Figure 24-59 shows a ring of outer radius $R = 13.0 \text{ cm}$, inner radius $r = 0.200R$, and uniform surface charge density $\sigma = 6.20 \text{ pC/m}^2$. With $V = 0$ at infinity, find the electric potential at point $P$ on the central axis of the ring, at distance $z = 2.00R$ from the center of the ring.

![Fig. 24-59](image)

** Problem 81 **
*Electron in a well.* Figure 24-60 shows electric potential $V$ along an $x$ axis. The scale of the vertical axis is set by $V_A = 8.0 \text{ V}$. An electron is to be released at $x = 4.5 \text{ cm}$ with initial kinetic energy $3.00 \text{ eV}$. (a) If it is initially moving in the positive direction of the axis, does it reach a turning point (if so, what is the $x$ coordinate of that point) or does it escape from the plotted region (if so, what is its speed at $x = 0$)? (b) If it is initially moving in the positive direction of the axis, does it reach a turning point (if so, what is the $x$ coordinate of that point) or does it escape from the plotted region (if so, what is its speed at $x = 7.0 \text{ cm}$)? What are the (c) magnitude $F$ and (d) direction (positive or negative direction of the $x$ axis) of the electric force on the electron if the electron moves just to the left of $x = 4.0 \text{ cm}$? What are (e) $F$ and (f) the direction if it moves just to the right of $x = 5.0 \text{ cm}$?

![Fig. 24-60](image)

** Problem 82 **
(a) If Earth had a uniform surface charge density of 1.0 electron/m$^2$ (a very artificial assumption), what would its potential be? (Set $V = 0$ at infinity.) What would be the (b) magnitude and (c) direction (radially inward or outward) of the electric field due to Earth just outside its surface?

** Problem 83 **
In Fig. 24-61, point $P$ is at distance $d_1 = 4.00 \text{ m}$ from particle 1 ($q_1 = -2e$) and distance $d_2 = 2.00 \text{ m}$ from particle 2 ($q_2 = +2e$), with both particles fixed in place. (a) With $V = 0$ at infinity, what is $V$ at $P$? If we bring a particle of charge $q_3 = +2e$ from infinity to $P$, (b) how much work do we do and (c) what is the potential energy of the three-particle system?

![Fig. 24-61](image)

** Problem 84 **
A solid conducting sphere of radius $3.0 \text{ cm}$ has a charge of $4.00 \text{ nC}$ distributed uniformly over its surface. Let $A$ be a point $1.0 \text{ cm}$ from the center of the sphere, $S$ be a point on the surface of the sphere, and $B$ be a point $5.0 \text{ cm}$ from the center of the sphere. What are the electric potential differences (a) $V_A - V_S$ and (b) $V_A - V_B$?

** Problem 85 **
In Fig. 24-62, we move a particle of charge $+2e$ in from infinity to the $x$ axis. How much work do we do? Distance $D$ is $4.00 \text{ m}$.

![Fig. 24-62](image)

** Problem 86 **
Figure 24-63 shows a hemisphere with a charge of $4.00 \mu \text{ C}$ distributed uniformly through its volume. The hemisphere lies on an $xy$ plane the way half a grapefruit might lie face down on a kitchen table. Point $P$ is located on the plane, along a radial line from the hemisphere’s center of curvature, at radial distance $15 \text{ cm}$. What is the electric potential at point $P$ due to the hemisphere?

![Fig. 24-63](image)

** Problem 87 **
*SSM* Three $+0.12 \text{ C}$ charges form an equilateral triangle 1.7 m on a side. Using energy supplied at the rate of 0.83 kW, how many days would be required to move one of the charges to the midpoint of the line joining the other two charges?
** View All Solutions Here **

88 Two charges \( q = \pm 2.0 \, \mu\text{C} \) are fixed a distance \( d = 2.0 \, \text{cm} \) apart (Fig. 24-64). (a) With \( V = 0 \) at infinity, what is the electric potential at point \( C \)? (b) You bring a third charge \( q = \pm 2.0 \, \mu\text{C} \) from infinity to \( C \). How much work must you do? (c) What is the potential energy \( U \) of the three-charge configuration when the third charge is in place?

90 A particle of positive charge \( Q \) is fixed at point \( P \). A second particle of mass \( m \) and negative charge \( -q \) moves at constant speed in a circle of radius \( r_1 \), centered at \( P \). Derive an expression for the work \( W \) that must be done by an external agent on the second particle to increase the radius of the circle of motion to \( r_2 \).

91 Two charged, parallel, flat conducting surfaces are spaced \( d = 1.0 \, \text{cm} \) apart and produce a potential difference \( \Delta V = 625 \, \text{V} \) between them. An electron is projected from one surface directly toward the second. What is the initial speed of the electron if it stops just at the second surface?

92 In Fig. 24-65, point \( P \) is at the center of the rectangle. With \( V = 0 \) at infinity, \( q_1 = 5.00 \, \text{fC} \), \( q_2 = 2.00 \, \text{fC} \), \( q_3 = 3.00 \, \text{fC} \), and \( d = 2.54 \, \text{cm} \), what is the net electric potential at \( P \) due to the six charged particles?

93 SSM A uniform charge of +16.0 \( \mu\text{C} \) is on a thin circular ring lying in an \( xy \) plane and centered on the origin. The ring’s radius is 3.00 cm. If point \( A \) is at the origin and point \( B \) is on the \( z \) axis at \( z = 4.00 \, \text{cm} \), what is \( V_{B} - V_{A} \)?

94 Consider a point charge \( q = 1.50 \times 10^{-8} \, \text{C} \), and take \( V = 0 \) at infinity. (a) What are the shape and dimensions of an equipotential surface having a potential of 30.0 V due to \( q \) alone? (b) Are surfaces whose potentials differ by a constant amount (1.0 V, say) evenly spaced?

95 SSM A thick spherical shell of charge \( Q \) and uniform volume charge density \( \rho \) is bounded by radii \( r_1 \) and \( r_2 \). With \( V = 0 \) at infinity, find the electric potential \( V \) as a function of distance \( r \) from the center of the distribution, considering regions (a) \( r > r_2 \), (b) \( r_2 > r > r_1 \), and (c) \( r < r_1 \) (d) Do these solutions agree with each other at \( r = r_2 \) and \( r = r_1 \)? (Hint: See Section 23-9.)

96 A charge \( q \) is distributed uniformly throughout a spherical volume of radius \( R \). Let \( V = 0 \) at infinity. What are (a) \( V \) at radial distance \( r < R \) and (b) the potential difference between points at \( r = R \) and the point at \( r = 0 \)?

97 Figure 24-35 shows two charged particles on an axis. Sketch the electric field lines and the equipotential surfaces in the plane of the page for (a) \( q_1 = +q, q_2 = +2q \) and (b) \( q_1 = +q, q_2 = -3q \).

98 What is the electric potential energy of the charge configuration of Fig. 24-8a? Use the numerical values provided in the associated sample problem.

99 (a) Using Eq. 24-32, show that the electric potential at a point on the central axis of a thin ring (of charge \( q \) and radius \( R \)) and at distance \( z \) from the ring is

\[
V = \frac{1}{4\pi\varepsilon_0} \frac{q}{\sqrt{x^2 + z^2 + R^2}}.
\]

(b) From this result, derive an expression for the electric field magnitude \( E \) at points on the ring’s axis; compare your result with the calculation of \( E \) in Section 22-6.

100 An alpha particle (which has two protons) is sent directly toward a target nucleus containing 92 protons. The alpha particle has an initial kinetic energy of 0.48 \( \text{MeV} \). What is the least center-to-center distance the alpha particle will be from the target nucleus, assuming the nucleus does not move?

101 In the quark model of fundamental particles, a proton is composed of three quarks: two “up” quarks, each having charge \( +2/3e \), and one “down” quark, having charge \( -e/3 \). Suppose that the three quarks are equidistant from one another. Take that separation distance to be 1.52 \( \times 10^{-15} \, \text{m} \) and calculate the electric potential energy of the system of (a) only the two up quarks and (b) all three quarks.

102 (a) A proton of kinetic energy \( 4.80 \, \text{MeV} \) travels head-on toward a lead nucleus. Assuming that the proton does not penetrate the nucleus and that the only force between proton and nucleus is the Coulomb force, calculate the smallest center-to-center separation \( d_p \) between proton and nucleus when the proton momentarily stops. If the proton were replaced with an alpha particle (which contains two protons) of the same initial kinetic energy, the alpha particle would stop at center-to-center separation \( d_{ap} \). (b) What is \( d_{ap}/d_p \)?

103 In Fig. 24-66, two particles of charges \( q_1 \) and \( q_2 \) are fixed to an \( x \) axis. If a third particle, of charge +6.0 \( \mu\text{C} \), is brought from an infinite distance to point \( P \), the three-particle system has the same electric potential energy as the original two-particle system. What is the charge ratio \( q_3/q_2 \)?

104 A charge of \( 1.50 \times 10^{-8} \, \text{C} \) lies on an isolated metal sphere of radius 16.0 cm. With \( V = 0 \) at infinity, what is the electric potential at points on the sphere’s surface?

105 SSM A solid copper sphere whose radius is 1.0 cm has a very thin surface coating of nickel. Some of the nickel atoms are radioactive, each atom emitting an electron as it decays. Half of these electrons enter the copper sphere, each depositing 100 \( \text{keV} \) of energy there. The other half of the electrons escape, each carrying away a charge \( -e \). The nickel coating has an activity of 3.70 \( \times 10^8 \) radioactive decays per second. The sphere is hung from a long, nonconducting string and isolated from its surroundings. (a) How long will it take for the potential of the sphere to increase by 1000 \( \text{V} \)? (b) How long will it take for the temperature of the sphere to increase by 5.0 \( \text{K} \) due to the energy deposited by the electrons? The heat capacity of the sphere is 14 \( \text{J/K} \).