sec. 21-4 Coulomb’s Law

1. Of the charge $Q$ initially on a tiny sphere, a portion $q$ is to be transferred to a second, nearby sphere. Both spheres can be treated as particles. For what value of $q/Q$ will the electrostatic force between the two spheres be maximized?

Answer:

0.500

2. Identical isolated conducting spheres 1 and 2 have equal charges and are separated by a distance that is large compared with their diameters (Fig. 21-21a). The electrostatic force acting on sphere 2 due to sphere 1 is $\vec{F}$. Suppose now that a third identical sphere 3, having an insulating handle and initially neutral, is touched first to sphere 1 (Fig. 21-21b), then to sphere 2 (Fig. 21-21c), and finally removed (Fig. 21-21d). The electrostatic force that now acts on sphere 2 has magnitude $F'$. What is the ratio $F'/F$?

Figure 21-21 Problem 2.

3. What must be the distance between point charge $q_1 = 26.0 \mu C$ and point charge $q_2 = -47.0 \mu C$ for the electrostatic force between them to have a magnitude of 5.70 N?

Answer:

1.39 m

4. In the return stroke of a typical lightning bolt, a current of $2.5 \times 10^4 \text{ A}$ exists for 20 $\mu s$. How much charge is transferred in this event?

5. A particle of charge $+3.00 \times 10^{-6} \text{ C}$ is 12.0 cm distant from a second particle of charge $-1.50 \times 10^{-6} \text{ C}$. Calculate the magnitude of the electrostatic force between the particles.

Answer:
Two equally charged particles are held \(3.2 \times 10^{-3}\) m apart and then released from rest. The initial acceleration of the first particle is observed to be \(7.0\) m/s\(^2\) and that of the second to be \(9.0\) m/s\(^2\). If the mass of the first particle is \(6.3 \times 10^{-7}\) kg, what are (a) the mass of the second particle and (b) the magnitude of the charge of each particle?

In Fig. 21-22, three charged particles lie on an x axis. Particles 1 and 2 are fixed in place. Particle 3 is free to move, but the net electrostatic force on it from particles 1 and 2 happens to be zero. If \(L_{23} = L_{12}\), what is the ratio \(q_1/q_2\)?

![Figure 21-22](Problems 7 and 40.)

Answer:

-4.00

In Fig. 21-23, three identical conducting spheres initially have the following charges: sphere A, \(4Q\); sphere B, \(-6Q\); and sphere C, 0. Spheres A and B are fixed in place, with a center-to-center separation that is much larger than the spheres. Two experiments are conducted. In experiment 1, sphere C is touched to sphere A and then (separately) to sphere B, and then it is removed. In experiment 2, starting with the same initial states, the procedure is reversed: Sphere C is touched to sphere B and then (separately) to sphere A, and then it is removed. What is the ratio of the electrostatic force between A and B at the end of experiment 2 to that at the end of experiment 1?

![Figure 21-23](Problems 8 and 65.)

Answer:

(a) -1.00 \(\mu\)C; (b) 3.00 \(\mu\)C

Two identical conducting spheres, fixed in place, attract each other with an electrostatic force of 0.108 N when their center-to-center separation is 50.0 cm. The spheres are then connected by a thin conducting wire. When the wire is removed, the spheres repel each other with an electrostatic force of 0.0360 N. Of the initial charges on the spheres, with a positive net charge, what was (a) the negative charge on one of them and (b) the positive charge on the other?

Answer:

(a) -1.00 \(\mu\)C; (b) 3.00 \(\mu\)C

In Fig. 21-24, four particles form a square. The charges are \(q_1 = q_4 = Q\) and \(q_2 = q_3 = q\). (a) What is \(Q/q\) if the net electrostatic force on particles 1 and 4 is zero? (b) Is there any value of \(q\) that makes the net electrostatic force on each of the four particles zero? Explain.
Figure 21-24 Problems 10, 11, and 70.

11. In Fig. 21-24, the particles have charges \( q_1 = -q_2 = 100 \text{ nC} \) and \( q_3 = -q_4 = 200 \text{ nC} \), and distance \( a = 5.0 \text{ cm} \). What are the (a) \( x \) and (b) \( y \) components of the net electrostatic force on particle 3?

Answer:

(a) 0.17 N; (b) -0.046 N

12. Two particles are fixed on an \( x \) axis. Particle 1 of charge 40 \( \mu \text{C} \) is located at \( x = -2.0 \text{ cm} \); particle 2 of charge \( Q \) is located at \( x = 3.0 \text{ cm} \). Particle 3 of charge magnitude 20 \( \mu \text{C} \) is released from rest on the \( y \) axis at \( y = 2.0 \text{ cm} \). What is the value of \( Q \) if the initial acceleration of particle 3 is in the positive direction of (a) the \( x \) axis and (b) the \( y \) axis?

13. In Fig. 21-25, particle 1 of charge +1.0 \( \mu \text{C} \) and particle 2 of charge -3.0 \( \mu \text{C} \) are held at separation \( L = 10.0 \text{ cm} \) on an \( x \) axis. If particle 3 of unknown charge \( q_3 \) is to be located such that the net electrostatic force on it from particles 1 and 2 is zero, what must be the (a) \( x \) and (b) \( y \) coordinates of particle 3?

Answer:

(a) -14 cm; (b) 0

14. Three particles are fixed on an \( x \) axis. Particle 1 of charge \( q_1 \) is at \( x = -a \), and particle 2 of charge \( q_2 \) is at \( x = +a \). If their net electrostatic force on particle 3 of charge +\( Q \) is to be zero, what must be the ratio \( q_1/q_2 \) when particle 3 is at (a) \( x = +0.500a \) and (b) \( x = +1.50a \)?

15. The charges and coordinates of two charged particles held fixed in an \( xy \) plane are \( q_1 = +3.0 \text{ \mu C} \), \( x_1 = 3.5 \text{ cm} \), \( y_1 = 0.50 \text{ cm} \), and \( q_2 = -4.0 \text{ \mu C} \), \( x_2 = -2.0 \text{ cm} \), \( y_2 = 1.5 \text{ cm} \). Find the (a) magnitude and (b) direction of the electrostatic force on particle 2 due to particle 1. At what (c) \( x \) and (d) \( y \) coordinates should a third particle of charge \( q_3 = +4.0 \text{ \mu C} \) be placed such that the net electrostatic force on particle 2 due to particles 1 and 3 is zero?

Answer:
(a) 35 N; (b) -10°; (c) -8.4 cm; (d) +2.7 cm

16 In Fig. 21-26a, particle 1 (of charge $q_1$) and particle 2 (of charge $q_2$) are fixed in place on an x axis, 8.00 cm apart. Particle 3 (of charge $q_3 = +8.00 \times 10^{-19}$ C) is to be placed on the line between particles 1 and 2 so that they produce a net electrostatic force $F_{\text{3,net}}$ on it. Figure 21-26b gives the $x$ component of that force versus the coordinate $x$ at which particle 3 is placed. The scale of the $x$ axis is set by $x_s = 8.0$ cm. What are (a) the sign of charge $q_1$ and (b) the ratio $q_2 / q_1$?

![Figure 21-26](a) (b)

17 In Fig. 21-27a, particles 1 and 2 have charge $20.0 \, \mu C$ each and are held at separation distance $d = 1.50 \, m$. (a) What is the magnitude of the electrostatic force on particle 1 due to particle 2? In Fig. 21-27b, particle 3 of charge $20.0 \, \mu C$ is positioned so as to complete an equilateral triangle. (b) What is the magnitude of the net electrostatic force on particle 1 due to particles 2 and 3?

![Figure 21-27](a) (b)

18 In Fig. 21-28a, three positively charged particles are fixed on an x axis. Particles $B$ and $C$ are so close to each other that they can be considered to be at the same distance from particle $A$. The net force on particle $A$ due to particles $B$ and $C$ is $2.014 \times 10^{-23} \, N$ in the negative direction of the $x$ axis. In Fig. 21-28b, particle $B$ has been moved to the opposite side of $A$ but is still at the same distance from it. The net force on $A$ is now $2.877 \times 10^{-24} \, N$ in the negative direction of the $x$ axis. What is the ratio $q_C / q_B$?

![Figure 21-28](a) (b)

Answer:
(a) 1.60 N; (b) 2.77 N
In Fig. 21-25, particle 1 of charge $q$ and particle 2 of charge $+4.00q$ are held at separation $L = 9.00$ cm on an $x$ axis. If particle 3 of charge $q_3$ is to be located such that the three particles remain in place when released, what must be the (a) $x$ and (b) $y$ coordinates of particle 3, and (c) the ratio $q_3/q$?

Answer:
(a) 3.00 cm; (b) 0; (c) -0.444

Figure 21-29 shows an arrangement of three charged particles separated by distance $d$. Particles $A$ and $C$ are fixed on the $x$ axis, but particle $B$ can be moved along a circle centered on particle $A$. During the movement, a radial line between $A$ and $B$ makes an angle $\theta$ relative to the positive direction of the $x$ axis (Fig. 21-29b). The curves in Fig. 21-29c give, for two situations, the magnitude $F_{\text{net}}$ of the net electrostatic force on particle $A$ due to the other particles. That net force is given as a function of angle $\theta$ and as a multiple of a basic amount $F_0$. For example on curve 1, at $\theta = 180^\circ$, we see that $F_{\text{net}} = 2F_0$. (a) For the situation corresponding to curve 1, what is the ratio of the charge of particle $C$ to that of particle $B$ (including sign)? (b) For the situation corresponding to curve 2, what is that ratio?

![Figure 21-29](image)

Problem 20.

A nonconducting spherical shell, with an inner radius of 4.0 cm and an outer radius of 6.0 cm, has charge spread nonuniformly through its volume between its inner and outer surfaces. The volume charge density $\rho$ is the charge per unit volume, with the unit coulomb per cubic meter. For this shell $\rho = b/r$, where $r$ is the distance in meters from the center of the shell and $b = 3.0 \, \mu$C/m$^2$. What is the net charge in the shell?

Answer:
$3.8 \times 10^{-8}$ C

Figure 21-30 shows an arrangement of four charged particles, with angle $\theta = 30.0^\circ$ and distance $d = 2.00$ cm. Particle 2 has charge $q_2 = +8.00 \times 10^{-19}$ C; particles 3 and 4 have charges $q_3 = q_4 = -1.60 \times 10^{-19}$ C. (a) What is distance $D$ between the origin and particle 2 if the net electrostatic force on particle 1 due to the other particles is zero? (b) If particles 3 and 4 were moved closer to the $x$ axis but maintained their symmetry about that axis, would the required value of $D$ be greater than, less than, or the same as in part (a)?

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**19 SSM WWW**

**20**

**21**

**22**
Problem 22.

In Fig. 21-31, particles 1 and 2 of charge \( q_1 = q_2 = +3.20 \times 10^{-19} \) C are on a y axis at distance \( d = 17.0 \) cm from the origin. Particle 3 of charge \( q_3 = +6.40 \times 10^{-19} \) C is moved gradually along the x axis from \( x = 0 \) to \( x = +5.0 \) m. At what values of \( x \) will the magnitude of the electrostatic force on the third particle from the other two particles be (a) minimum and (b) maximum? What are the (c) minimum and (d) maximum magnitudes?

Answer:

(a) 0; (b) 12 cm; (c) 0; (d) \( 4.9 \times 10^{-26} \) N

sec. 21-5 Charge is Quantized

•24 Two tiny, spherical water drops, with identical charges of \(-1.00 \times 10^{-16} \) C, have a center-to-center separation of 1.00 cm. (a) What is the magnitude of the electrostatic force acting between them? (b) How many excess electrons are on each drop, giving it its charge imbalance?

Answer:

6.3 \times 10^{11}

•26 What is the magnitude of the electrostatic force between a singly charged sodium ion (Na\(^+\), of charge +e) and an adjacent singly charged chlorine ion (Cl\(^-\), of charge -e) in a salt crystal if their separation is \( 2.82 \times 10^{-10} \) m?

•27 SSM The magnitude of the electrostatic force between two identical ions that are separated by a distance of \( 5.0 \times 10^{-10} \) m is \( 3.7 \times 10^{-9} \) N. (a) What is the charge of each ion? (b) How many electrons are “missing” from each ion (thus giving the ion its charge imbalance)?

Answer:

(a) \( 3.2 \times 10^{-19} \) C; (b) 2
A current of 0.300 A through your chest can send your heart into fibrillation, ruining the normal rhythm of heartbeat and disrupting the flow of blood (and thus oxygen) to your brain. If that current persists for 2.00 min, how many conduction electrons pass through your chest?

In Fig. 21-32, particles 2 and 4, of charge \(-e\), are fixed in place on a y axis, at \(y_2 = -10.0\) cm and \(y_4 = 5.00\) cm. Particles 1 and 3, of charge \(-e\), can be moved along the x axis. Particle 5, of charge \(+e\), is fixed at the origin. Initially particle 1 is at \(x_1 = -10.0\) cm and particle 3 is at \(x_3 = 10.0\) cm. (a) To what \(x\) value must particle 1 be moved to rotate the direction of the net electric force \(\vec{F}_{\text{net}}\) on particle 5 by 30° counterclockwise? (b) With particle 1 fixed at its new position, to what \(x\) value must you move particle 3 to rotate \(\vec{F}_{\text{net}}\) back to its original direction?

![Figure 21-32](image)

**Problem 29.**

**Answer:**

(a) -6.05 cm; (b) 6.05 cm

In Fig. 21-25, particles 1 and 2 are fixed in place on an x axis, at a separation of \(L = 8.00\) cm. Their charges are \(q_1 = +e\) and \(q_2 = -27e\). Particle 3 with charge \(q_3 = +4e\) is to be placed on the line between particles 1 and 2, so that they produce a net electrostatic force \(\vec{F}_{\text{3,net}}\) on it. (a) At what coordinate should particle 3 be placed to minimize the magnitude of that force? (b) What is that minimum magnitude?

**Problem 30.**

**Answer:**

122 mA

Earth’s atmosphere is constantly bombarded by cosmic ray protons that originate somewhere in space. If the protons all passed through the atmosphere, each square meter of Earth’s surface would intercept protons at the average rate of 1500 protons per second. What would be the electric current intercepted by the total surface area of the planet?

**Problem 31.**

**Answer:**

122 mA

Figure 21-33a shows charged particles 1 and 2 that are fixed in place on an x axis. Particle 1 has a charge with a magnitude of \([q_1] = 8.00e\). Particle 3 of charge \(q_3 = +8.00e\) is initially on the x axis near particle 2. Then particle 3 is gradually moved in the positive direction of the x axis. As a result, the magnitude of the net electrostatic force \(\vec{F}_{\text{2,net}}\) on particle 2 due to particles 1 and 3 changes. Figure 21-33b gives the x component of that net force as a function of the position \(x\) of particle 3. The scale of the x axis is set by \(x_0 = 0.80\) m. The plot has an asymptote of \(F_{2,\text{net}} = 1.5 \times 10^{-25}\) N as \(x \to \infty\). As a multiple of \(e\) and including the sign, what is the charge \(q_2\) of particle 2?
Problem 32.

Calculate the number of coulombs of positive charge in 250 cm$^3$ of (neutral) water. (Hint: A hydrogen atom contains one proton; an oxygen atom contains eight protons.)

Answer:

$1.3 \times 10^7$ C

Problem 34.

Figure 21-34 shows electrons 1 and 2 on an $x$ axis and charged ions 3 and 4 of identical charge $-q$ and at identical angles $\theta$. Electron 2 is free to move; the other three particles are fixed in place at horizontal distances $R$ from electron 2 and are intended to hold electron 2 in place. For physically possible values of $q \leq 5e$, what are the (a) smallest, (b) second smallest, and (c) third smallest values of $\theta$ for which electron 2 is held in place?

Figure 21-35

In crystals of the salt cesium chloride, cesium ions Cs$^+$ form the eight corners of a cube and a chlorine ion Cl$^-$ is at the cube's center (Fig. 21-35). The edge length of the cube is 0.40 nm. The Cs$^+$ ions are each deficient by one electron (and thus each has a charge of $+e$), and the Cl$^-$ ion has one excess electron (and thus has a charge of $-e$). (a) What is the magnitude of the net electrostatic force exerted on the Cl$^-$ ion by the eight Cs$^+$ ions at the corners of the cube? (b) If one of the Cs$^+$ ions is missing, the crystal is said to have a defect; what is the magnitude of the net electrostatic force exerted on the Cl$^-$ ion by the seven remaining Cs$^+$ ions?
Problem 35.

Answer:

(a) 0; (b) \(1.9 \times 10^{-9}\text{ N}\)

sec. 21-6 Charge is Conserved

Electrons and positrons are produced by the nuclear transformations of protons and neutrons known as beta decay. (a) If a proton transforms into a neutron, is an electron or a positron produced? (b) If a neutron transforms into a proton, is an electron or a positron produced?

Identify X in the following nuclear reactions: (a) \(^1\text{H} + ^{9}\text{Be} \rightarrow \text{X} + \text{n}\); (b) \(^{12}\text{C} + ^1\text{H} \rightarrow \text{X}\); (c) \(^{15}\text{N} + ^1\text{H} \rightarrow ^4\text{He} + \text{X}\). Appendix F will help.

Answer:

(a) \(^9\text{B}\); (b) \(^{13}\text{N}\); (c) \(^{12}\text{C}\)

Additional Problems

Figure 21-36 shows four identical conducting spheres that are actually well separated from one another. Sphere W (with an initial charge of zero) is touched to sphere A and then they are separated. Next, sphere W is touched to sphere B (with an initial charge of -32e) and then they are separated. Finally, sphere W is touched to sphere C (with an initial charge of +48e), and then they are separated. The final charge on sphere W is +18e. What was the initial charge on sphere A?

\[A \quad B \quad C \quad W\]

Problem 38.

In Fig. 21-37, particle 1 of charge +4e is above a floor by distance \(d_1 = 2.00\text{ mm}\) and particle 2 of charge +6e is on the floor, at distance \(d_2 = 6.00\text{ mm}\) horizontally from particle 1. What is the \(x\) component of the electrostatic force on particle 2 due to particle 1?
Figure 21-37 Problem 39.

Answer:

\[ 1.31 \times 10^{-22} \text{ N} \]

40 In Fig. 21-22, particles 1 and 2 are fixed in place, but particle 3 is free to move. If the net electrostatic force on particle 3 due to particles 1 and 2 is zero and \( L_{23} = 2.00 L_{12} \), what is the ratio \( q_1/q_2 \)?

41 What equal positive charges would have to be placed on Earth and on the Moon to neutralize their gravitational attraction? (b) Why don’t you need to know the lunar distance to solve this problem? (c) How many kilograms of hydrogen ions (that is, protons) would be needed to provide the positive charge calculated in (a)?

Answer:

(a) \( 5.7 \times 10^{13} \) C; (b) cancels out; (c) \( 6.0 \times 10^5 \) kg

42 In Fig. 21-38, two tiny conducting balls of identical mass \( m \) and identical charge \( q \) hang from nonconducting threads of length \( L \). Assume that \( \theta \) is so small that \( \tan \theta \) can be replaced by its approximate equal, \( \sin \theta \) (a) Show that

\[ x = \left( \frac{q^2 L}{2 \pi \epsilon_0 m g} \right)^{1/3} \]

gives the equilibrium separation \( x \) of the balls. (b) If \( L = 120 \text{ cm}, m = 10 \text{ g}, \) and \( x = 5.0 \text{ cm} \), what is \( |q| \)?

Figure 21-38 Problems 42 and 43.

43 Explain what happens to the balls of Problem 42 if one of them is discharged (loses its charge \( q \) to, say, the ground). (b) Find the new equilibrium separation \( x \), using the given values of \( L \) and \( m \) and the computed value of \( |q| \).

Answer:

(b) 3.1 cm
How far apart must two protons be if the magnitude of the electrostatic force acting on either one due to the other is equal to the magnitude of the gravitational force on a proton at Earth's surface?

How many megacoulombs of positive charge are in 1.00 mol of neutral molecular-hydrogen gas (H₂)?

Answer: 0.19 MC

In Fig. 21-39, four particles are fixed along an x axis, separated by distances \( d = 2.00 \) cm. The charges are \( q_1 = +2e, q_2 = -e, q_3 = -e, \) and \( q_4 = +4e, \) with \( e = 1.60 \times 10^{-19} \) C. In unit-vector notation, what is the net electrostatic force on (a) particle 1 and (b) particle 2 due to the other particles?

![Figure 21-39](Problem 46)

Point charges of +6.0 \( \mu \)C and -4.0 \( \mu \)C are placed on an x axis, at \( x = 8.0 \) m and \( x = 16 \) m, respectively. What charge must be placed at \( x = 24 \) m so that any charge placed at the origin would experience no electrostatic force?

Answer: -45 \( \mu \)C

In Fig. 21-40, three identical conducting spheres form an equilateral triangle of side length \( d = 20.0 \) cm. The sphere radii are much smaller than \( d, \) and the sphere charges are \( q_A = -2.00 \) nC, \( q_B = -4.00 \) nC, and \( q_C = +8.00 \) nC. (a) What is the magnitude of the electrostatic force between spheres A and C? The following steps are then taken: A and B are connected by a thin wire and then disconnected; B is grounded by the wire, and the wire is then removed; B and C are connected by the wire and then disconnected. What now are the magnitudes of the electrostatic force (b) between spheres A and C and (c) between spheres B and C?

![Figure 21-40](Problem 48)

A neutron consists of one “up” quark of charge \( +2e/3 \) and two “down” quarks each having charge \( -e/3. \) If we assume that the down quarks are \( 2.6 \times 10^{15} \) m apart inside the neutron, what is the magnitude of the electrostatic force between them?

Answer: 3.8 N

Figure 21-41 shows a long, nonconducting, massless rod of length \( L, \) pivoted at its center and
balanced with a block of weight $W$ at a distance $x$ from the left end. At the left and right ends of the rod are attached small conducting spheres with positive charges $q$ and $2q$, respectively. A distance $h$ directly beneath each of these spheres is a fixed sphere with positive charge $Q$. (a) Find the distance $x$ when the rod is horizontal and balanced. (b) What value should $h$ have so that the rod exerts no vertical force on the bearing when the rod is horizontal and balanced?

![Figure 21-41 Problem 50.](image)

**51** A charged nonconducting rod, with a length of 2.00 m and a cross-sectional area of 4.00 cm$^2$, lies along the positive side of an $x$ axis with one end at the origin. The volume charge density $\rho$ is charge per unit volume in coulombs per cubic meter. How many excess electrons are on the rod if $\rho$ is (a) uniform, with a value of $-4.00 \, \mu\text{C/m}^3$, and (b) nonuniform, with a value given by $\rho = bx^2$, where $b = -2.00 \, \mu\text{C/m}^3$?

**Answer:**

(a) $2.00 \times 10^{10}$ electrons; (b) $1.33 \times 10^{10}$ electrons

**52** A particle of charge $Q$ is fixed at the origin of an $xy$ coordinate system. At $t = 0$ a particle ($m = 0.800$ g, $q = 4.00 \, \mu\text{C}$) is located on the $x$ axis at $x = 20.0$ cm, moving with a speed of 50.0 m/s in the positive $y$ direction. For what value of $Q$ will the moving particle execute circular motion? (Neglect the gravitational force on the particle.)

**Answer:**

What would be the magnitude of the electrostatic force between two 1.00 C point charges separated by a distance of (a) 1.00 m and (b) 1.00 km if such point charges existed (they do not) and this configuration could be set up?

**Answer:**

(a) $8.99 \times 10^9$ N; (b) $8.99$ kN

**54** A charge of 6.0 $\mu$C is to be split into two parts that are then separated by 3.0 mm. What is the maximum possible magnitude of the electrostatic force between those two parts?

**55** Of the charge $Q$ on a tiny sphere, a fraction $a$ is to be transferred to a second, nearby sphere. The spheres can be treated as particles. (a) What value of $a$ maximizes the magnitude $F$ of the electrostatic force between the two spheres? What are the (b) smaller and (c) larger values of $a$ that put $F$ at half the maximum magnitude?

**Answer:**

(a) 0.5; (b) 0.15; (c) 0.85

**56** If a cat repeatedly rubs against your cotton slacks on a dry day, the charge transfer between the cat hair and the cotton can leave you with an excess charge of $-2.00 \, \mu\text{C}$. (a) How many electrons are transferred between you and the cat?
You will gradually discharge via the floor, but if instead of waiting, you immediately reach toward a faucet, a painful spark can suddenly appear as your fingers near the faucet. (b) In that spark, do electrons flow from you to the faucet or vice versa? (c) Just before the spark appears, do you induce positive or negative charge in the faucet? (d) If, instead, the cat reaches a paw toward the faucet, which way do electrons flow in the resulting spark? (e) If you stroke a cat with a bare hand on a dry day, you should take care not to bring your fingers near the cat's nose or you will hurt it with a spark. Considering that cat hair is an insulator, explain how the spark can appear.

57 We know that the negative charge on the electron and the positive charge on the proton are equal. Suppose, however, that these magnitudes differ from each other by 0.00010%. With what force would two copper coins, placed 1.0 m apart, repel each other? Assume that each coin contains $3 \times 10^{22}$ copper atoms. (Hint: A neutral copper atom contains 29 protons and 29 electrons.) What do you conclude?

Answer:

$1.7 \times 10^8$ N

58 In Fig. 21-25, particle 1 of charge -80.0 $\mu$C and particle 2 of charge +40.0 $\mu$C are held at separation $L = 20.0$ cm on an x axis. In unit-vector notation, what is the net electrostatic force on particle 3, of charge $q_3 = 20.0$ $\mu$C, if particle 3 is placed at (a) $x = 40.0$ cm and (b) $x = 80.0$ cm? What should be the (c) x and (d) y coordinates of particle 3 if the net electrostatic force on it due to particles 1 and 2 is zero?

59 What is the total charge in coulombs of 75.0 kg of electrons?

Answer:

$-1.32 \times 10^{13}$ C

60 In Fig. 21-42, six charged particles surround particle 7 at radial distances of either $d = 1.0$ cm or $2d$, as drawn. The charges are $q_1 = +2e$, $q_2 = +4e$, $q_3 = +e$, $q_4 = +4e$, $q_5 = +2e$, $q_6 = +8e$, $q_7 = +6e$, with $e = 1.60 \times 10^{-19}$ C. What is the magnitude of the net electrostatic force on particle 7?

61 Three charged particles form a triangle: particle 1 with charge $Q_1 = 80.0$ nC is at xy coordinates (0, 3.00 mm), particle 2 with charge $Q_2$ is at (0, -3.00 mm), and particle 3 with charge $q = 18.0$ nC is at (4.00 mm, 0). In unit-vector notation, what is the electrostatic force on particle 3 due to the other two particles if $Q_2$ is equal to (a) 80.0 nC and (b) -80.0 nC?

Answer:

(a) $(0.829N)i$; (b) $(-0.621N)j$
62 SSM In Fig. 21-43, what are the (a) magnitude and (b) direction of the net electrostatic force on particle 4 due to the other three particles? All four particles are fixed in the xy plane, and \( q_1 = -3.20 \times 10^{-19} \) C, \( q_2 = +3.20 \times 10^{-19} \) C, \( q_3 = +6.40 \times 10^{-19} \) C, \( q_4 = +3.20 \times 10^{-19} \) C, \( \theta_1 = 35.0^\circ \), \( d_1 = 3.00 \) cm, and \( d_2 = d_3 = 2.00 \) cm.

\[
\begin{align*}
\text{Figure 21-43} & \quad \text{Problem 62.}
\end{align*}
\]

63 Two point charges of 30 nC and -40 nC are held fixed on an x axis, at the origin and at \( x = 72 \) cm, respectively. A particle with a charge of 42 \( \mu \)C is released from rest at \( x = 28 \) cm. If the initial acceleration of the particle has a magnitude of 100 km/s\(^2\), what is the particle's mass?

Answer:

\[2.2 \times 10^{-6} \text{ kg}\]

64 Two small, positively charged spheres have a combined charge of \( 5.0 \times 10^{-5} \) C. If each sphere is repelled from the other by an electrostatic force of 1.0 N when the spheres are 2.0 m apart, what is the charge on the sphere with the smaller charge?

65 The initial charges on the three identical metal spheres in Fig. 21-23 are the following: sphere A, \( Q \); sphere B, \(-Q/4\); and sphere C, \( Q/2 \), where \( Q = 2.00 \times 10^{-14} \) C. Spheres A and B are fixed in place, with a center-to-center separation of \( d = 1.20 \) m, which is much larger than the spheres. Sphere C is touched first to sphere A and then to sphere B and is then removed. What then is the magnitude of the electrostatic force between spheres A and B?

Answer:

\[4.68 \times 10^{-19} \text{ N}\]

66 An electron is in a vacuum near Earth's surface and located at \( y = 0 \) on a vertical y axis. At what value of \( y \) should a second electron be placed such that its electrostatic force on the first electron balances the gravitational force on the first electron?

67 SSM In Fig. 21-25, particle 1 of charge \(-5.00q\) and particle 2 of charge \(+2.00q\) are held at separation \( L \) on an x axis. If particle 3 of unknown charge \( q_3 \) is to be located such that the net electrostatic force on it from particles 1 and 2 is zero, what must be the (a) \( x \) and (b) \( y \) coordinates of particle 3?

Answer:

(a) \( 2.72L \); (b) 0

68 Two engineering students, John with a mass of 90 kg and Mary with a mass of 45 kg, are 30 m apart. Suppose each has a 0.01% imbalance in the amount of positive and negative charge, one
student being positive and the other negative. Find the order of magnitude of the electrostatic force of attraction between them by replacing each student with a sphere of water having the same mass as the student.

69 In the radioactive decay of Eq. 21-13, a \(^{238}\text{U}\) nucleus transforms to \(^{234}\text{Th}\) and an ejected \(^{4}\text{He}\). (These are nuclei, not atoms, and thus electrons are not involved.) When the separation between \(^{234}\text{Th}\) and \(^{4}\text{He}\) is \(9.0 \times 10^{-15}\) m, what are the magnitudes of (a) the electrostatic force between them and (b) the acceleration of the \(^{4}\text{He}\) particle?

Answer:

(a) \(5.1 \times 10^2\) N; (b) \(7.7 \times 10^{28}\) m/s\(^2\)

70 In Fig. 21-24, four particles form a square. The charges are \(q_1 = +Q,\) \(q_2 = q_3 = q,\) and \(q_4 = -2.00Q.\) What is \(q/Q\) if the net electrostatic force on particle 1 is zero?

sec. 22-3 Electric Field Lines

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

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

Figure 22-29 Problem 2.

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

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

Answer:

(a) \(3.07 \times 10^{21}\) N/C; (b) outward

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

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

**Answer:**

56 pC

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

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

**Answer:**

\[
\left(1.02 \times 10^5 \text{ N/C}\right) \hat{j}
\]

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

**Answer:**

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

Answer:

(a) $1.38 \times 10^{-10}$ N/C; (b) $180^\circ$

Problem 10.

Two particles are fixed to an $x$ axis: particle 1 of charge $q_1 = 2.1 \times 10^{-8}$ C at $x = 20$ cm and particle 2 of charge $q_2 = -4.00q_1$ at $x = 70$ cm. At what coordinate on the axis is the net electric field produced by the particles equal to zero?

Answer:

- $30$ cm.

Problem 11.

Two particles are fixed to an $x$ axis: particle 1 of charge $q_1 = 2.1 \times 10^{-8}$ C at $x = 20$ cm and particle 2 of charge $q_2 = -4.00q_1$ at $x = 70$ cm. At what coordinate on the axis is the net electric field produced by the particles equal to zero?

Answer:

- $30$ cm.

Problem 12.

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

Figure 22-34

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

Answer:

(a) $3.60 \times 10^{-6}$ N/C; (b) $2.55 \times 10^{-6}$ N/C; (c) $3.60 \times 10^{-4}$ N/C; (d) $7.09 \times 10^{-7}$ N/C; (e) As the proton nears the disk, the forces on it from electrons $e_s$ more nearly cancel.

Problem 13.

- Figure 22-35

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

Answer:

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

Answer:

(a) 160 N/C; (b) 45°

Figure 22-38 shows a plastic ring of radius $R = 50.0$ cm. Two small charged beads are on the ring: Bead 1 of charge $+2.00 \mu C$ is fixed in place at the left side; bead 2 of charge $+6.00 \mu C$ can be moved along the ring. The two beads produce a net electric field of magnitude $E$ at the center of the ring. At what (a) positive and (b) negative value of angle $\theta$ should bead 2 be positioned such that $E = 2.00 \times 10^5$ N/C?

Problem 16.

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

Answer:

(a) -90°; (b) +2.0 μC; (c) -1.6 μC

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

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

\[
E = \frac{1}{2\pi} \frac{qd}{r^3} + E_{\text{next}}
\]

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

Answer:

(a) \( qd/4\pi\varepsilon_0 r^3 \); (b) -90°
Equations 22-8 and 22-9 are approximations of the magnitude of the electric field of an electric dipole, at points along the dipole axis. Consider a point $P$ on that axis at distance $z = 5.00d$ from the dipole center ($d$ is the separation distance between the particles of the dipole). Let $E_{\text{appr}}$ be the magnitude of the field at point $P$ as approximated by Eqs. 22-8 and 22-9. Let $E_{\text{act}}$ be the actual magnitude. What is the ratio $E_{\text{appr}}/E_{\text{act}}$?

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

$$E = \frac{3Q}{4\pi \varepsilon_0 z^4},$$

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

![Diagram of a quadrupole with points $P$, $d$, and $z$.](image)

Figure 22-41 Problem 21.

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

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

Problem 23.

Answer:

0.506
**24** A thin nonconducting rod with a uniform distribution of positive charge $Q$ is bent into a circle of radius $R$ (Fig. 22-43). The central perpendicular axis through the ring is a $z$ axis, with the origin at the center of the ring. What is the magnitude of the electric field due to the rod at (a) $z = 0$ and (b) $z = \infty$? (c) In terms of $R$, at what positive value of $z$ is that magnitude maximum? (d) If $R = 2.00$ cm and $Q = 4.00 \mu$C, what is the maximum magnitude?

**Figure 22-43** Problem 24.

**25** Figure 22-44 shows three circular arcs centered on the origin of a coordinate system. On each arc, the uniformly distributed charge is given in terms of $Q = 2.00 \mu$C. The radii are given in terms of $R = 10.0$ cm. What are the (a) magnitude and (b) direction (relative to the positive $x$ direction) of the net electric field at the origin due to the arcs?

**Figure 22-44** Problem 25.

**Answer:**

(a) $1.62 \times 10^6$ N/C; (b) -45°

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

**Figure 22-45** Problem 26.

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

\[
\begin{align*}
\text{Answer:} \quad & \quad \text{(a) 23.8 N/C; (b) -90°} \\
\end{align*}
\]

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

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

\[
\begin{align*}
\text{Answer:} \quad & \quad 1.57 \\
\end{align*}
\]

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

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

Answer:

(a) $5.19 \times 10^{-14}$ C/m; (b) $1.57 \times 10^{-3}$ N/C; (c) $180^\circ$; (d) $1.52 \times 10^{-8}$ N/C; (e) $1.52 \times 10^{-8}$ N/C

Problem 31.

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

Answer:

(a) $5.19 \times 10^{-14}$ C/m; (b) $1.57 \times 10^{-3}$ N/C; (c) $180^\circ$; (d) $1.52 \times 10^{-8}$ N/C; (e) $1.52 \times 10^{-8}$ N/C

Problem 32.

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

Answer:

(a) $5.90 \times 10^{-12}$ N/C; (b) $90^\circ$

Problem 33.

In Fig. 22-51, a “semi-infinite” nonconducting rod (that is, infinite in one direction only) has uniform linear charge density $\lambda$. Show that the electric field $\vec{E}_P$ at point $P$ makes an angle of $45^\circ$ with the rod and that this result is independent of the distance $R$. (Hint: Separately find the component of $\vec{E}_P$ parallel to the rod and the component perpendicular to the rod.)
sec. 22-7 The Electric Field Due to a Charged Disk

34 A disk of radius 2.5 cm has a surface charge density of 5.3 mC/m² on its upper face. What is the magnitude of the electric field produced by the disk at a point on its central axis at distance \( z = 12 \) cm from the disk?

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

Answer:

0.346 m

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

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

Answer:

28%

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

Figure 22-53

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

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

**Answer:**

$-5e$

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

**Answer:**

(a) $1.5 \times 10^3 \, N/C$; (b) $2.4 \times 10^{-16} \, N$; (c) up; (d) $1.6 \times 10^{-26} \, N$; (e) $1.5 \times 10^{10}$

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

**Answer:**

(a) $1.5 \times 10^3 \, N/C$; (b) $2.4 \times 10^{-16} \, N$; (c) up; (d) $1.6 \times 10^{-26} \, N$; (e) $1.5 \times 10^{10}$

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

**Answer:**

(a) $6.64 \times 10^{-27} \, kg$ and a charge of $+2e$. What are the (a) magnitude and (b) direction of the electric field that will balance the gravitational force on the particle?
**45 ILW** An electron on the axis of an electric dipole is 25 nm from the center of the dipole. What is the magnitude of the electrostatic force on the electron if the dipole moment is $3.6 \times 10^{-29}$ C · m? Assume that 25 nm is much larger than the dipole charge separation.

**Answer:**

$6.6 \times 10^{-15}$ N

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

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

**Answer:**

(a) $1.92 \times 10^{12}$ m/s$^2$; (b) $1.96 \times 10^5$ m/s

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

**Figure 22-54** Problem 48.

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

**Answer:**

(a) 0.245 N; (b) -11.3°; (c) 108 m; (d) -21.6 m

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

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

Answer:
2.6 × 10^{-10} N; (b) 3.1 × 10^{-8} N; (c) moves to stigma

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

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

Figure 22-55 Problem 53.

Answer:
27 \mu m

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

Figure 22-56 Problem 54.

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

Answer:

(a) \( 2.7 \times 10^6 \) m/s; (b) 1.0 kN/C

**sec. 22-9 A Dipole in an Electric Field**

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

Answer:

(a) \( 9.30 \times 10^{-15} \) C·m; (b) \( 2.05 \times 10^{-11} \) J

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

Answer:

(a) \( 9.30 \times 10^{-15} \) C·m; (b) \( 2.05 \times 10^{-11} \) J

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

![Figure 22-57 Problem 58.](image)

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

Answer:

\( 1.22 \times 10^{-23} \) J

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

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

**Answer:**

\[
\left( \frac{1}{2\pi} \right) \left( \frac{pE}{I} \right)^{0.5}
\]

**Additional Problems**

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

63 A spherical water drop 1.20 \( \mu \)m in diameter is suspended in calm air due to a downward-directed atmospheric electric field of magnitude \( E = 462 \) N/C. (a) What is the magnitude of the gravitational force on the drop? (b) How many excess electrons does it have?

**Answer:**

(a) \( 8.87 \times 10^{-15} \) N; (b) 120

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

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

(Hint: You will probably resort to a graphical solution.)

**Answer:**

217°

66 A proton and an electron form two corners of an equilateral triangle of side length 2.0 \( \times 10^{-6} \) m. What is the magnitude of the net electric field these two particles produce at the third corner?
67 A charge (uniform linear density = 9.0 nC/m) lies on a string that is stretched along an x axis from x = 0 to x = 3.0 m. Determine the magnitude of the electric field at x = 4.0 m on the x axis.

Answer:
61 N/C

68 In Fig. 22-60, eight particles form a square in which distance d = 2.0 cm. The charges are q₁ = +3e, q₂ = +e, q₃ = -5e, q₄ = -2e, q₅ = +3e, q₆ = +e, q₇ = -5e, and q₈ = +e. In unit-vector notation, what is the net electric field at the square’s center?

![Figure 22-60](image)

Figure 22-60 Problem 68.

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

Answer:
(a) 47 N/C; (b) 27 N/C

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

<table>
<thead>
<tr>
<th>q (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.563 × 10⁻¹⁹</td>
</tr>
<tr>
<td>13.13 × 10⁻¹⁹</td>
</tr>
<tr>
<td>19.71 × 10⁻¹⁹</td>
</tr>
<tr>
<td>8.204 × 10⁻¹⁹</td>
</tr>
<tr>
<td>16.48 × 10⁻¹⁹</td>
</tr>
<tr>
<td>22.89 × 10⁻¹⁹</td>
</tr>
<tr>
<td>11.50 × 10⁻¹⁹</td>
</tr>
<tr>
<td>18.08 × 10⁻¹⁹</td>
</tr>
<tr>
<td>26.13 × 10⁻¹⁹</td>
</tr>
</tbody>
</table>

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

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

Answer:
38 N/C

72 An electron is constrained to the central axis of the ring of charge of radius R in Fig. 22-10, with z ≪ R. Show that the electrostatic force on the electron can cause it to oscillate through the ring center with an angular frequency
\[ \omega = \sqrt{\frac{eq}{4\pi \varepsilon_0 mR^3}}, \]

where \( q \) is the ring’s charge and \( m \) is the electron’s mass.

**73 SSM** The electric field in an \( xy \) plane produced by a positively charged particle is

\[ 7.2 \{4.0\hat{i} + 3.0\hat{j}\} \text{N} / \text{C} \]
at the point (3.0, 3.0) cm and \( 100\hat{i} \text{N} / \text{C} \) at the point (2.0, 0) cm. What are the (a) \( x \) and (b) \( y \) coordinates of the particle? (c) What is the charge of the particle?

**Answer:**

(a) -1.0 cm; (b) 0; (c) 10 pC

**74** (a) What total (excess) charge \( q \) must the disk in Fig. 22-13 have for the electric field on the surface of the disk at its center to have magnitude \( 3.0 \times 10^6 \text{ N/C} \), the \( E \) value at which air breaks down electrically, producing sparks? Take the disk radius as 2.5 cm, and use the listing for air in Table 22-1. (b) Suppose each surface atom has an effective cross-sectional area of 0.015 nm\(^2\). How many atoms are needed to make up the disk surface? (c) The charge calculated in (a) results from some of the surface atoms having one excess electron. What fraction of these atoms must be so charged?

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

![Figure 22-61](Problems 75 and 86.)

**Answer:**

+1.00 \( \mu \text{C} \)

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

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

Answer:

(a) 6.0 mm; (b) 180°

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

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

Answer:

9:30

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

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

Answer:

(a) -0.029 C; (b) repulsive forces would explode the sphere

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

83 SSM An electric dipole with dipole moment

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

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

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

how much work is done by the agent?

Answer:
(a) $-1.49 \times 10^{-26}$ J; (b) $\left(-1.98 \times 10^{-26} N \cdot m\right) \hat{k}$; (c) $3.47 \times 10^{-26}$ J

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

![Figure 22-63 Problem 84.](image)

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

Answer:

(a) top row: 4, 8, 12; middle row: 5, 10, 14; bottom row: 7, 11, 16; (b) $1.63 \times 10^{19}$ C

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

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

![Figure 22-64 Problem 87.](image)

Answer:

(a) $(-1.80 \text{ N/C})\hat{i}$; (b) $(43.2 \text{ N/C})\hat{i}$; (c) $(-6.29 \text{ N/C})\hat{i}$

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

$$E = \frac{1}{4\pi \varepsilon_0} \frac{2q}{z^2}.$$
sec. 23-3 Flux of an Electric Field

1 SSM The square surface shown in Fig. 23-26 measures 3.2 mm on each side. It is immersed in a uniform electric field with magnitude \( E = 1800 \, \text{N/C} \) and with field lines at an angle of \( \theta = 35^\circ \) with a normal to the surface, as shown. Take that normal to be directed “outward,” as though the surface were one face of a box. Calculate the electric flux through the surface.

![Figure 23-26](image)

**Figure 23-26** Problem 1.

Answer:

\[-0.015 \, \text{N} \cdot \text{m}^2/\text{C}\]

2 An electric field given by \( \vec{E} = 4.0 \hat{i} - 3.0 (y^2 + 2.0) \hat{j} \) pierces a Gaussian cube of edge length 2.0 m and positioned as shown in Fig. 23-5. (The magnitude \( E \) is in newtons per coulomb and the position \( x \) is in meters.) What is the electric flux through the (a) top face, (b) bottom face, (c) left face, and (d) back face? (e) What is the net electric flux through the cube?

3 The cube in Fig. 23-27 has edge length 1.40 m and is oriented as shown in a region of uniform electric field. Find the electric flux through the right face if the electric field, in newtons per coulomb, is given by (a) \( 6.00 \hat{i} \), (b) \(-2.00 \hat{j} \), and (c) \(-3.00 \hat{i} + 4.00 \hat{k} \). (d) What is the total flux through the cube for each field?
sec. 23-4 Gauss' Law

In Fig. 23-28, a butterfly net is in a uniform electric field of magnitude $E = 3.0 \text{ mN/C}$. The rim, a circle of radius $a = 11 \text{ cm}$, is aligned perpendicular to the field. The net contains no net charge. Find the electric flux through the netting.

Answer:
(a) 0; (b) -3.92 N \cdot \text{m}^2/\text{C}; (c) 0; (d) 0

In Fig. 23-29, a proton is a distance $d/2$ directly above the center of a square of side $d$. What is the magnitude of the electric flux through the square? (Hint: Think of the square as one face of a cube with edge $d$.)

Answer:
$3.01 \text{ nN-m}^2/\text{C}$

At each point on the surface of the cube shown in Fig. 23-27, the electric field is parallel to the $z$ axis. The length of each edge of the cube is 3.0 m. On the top face of the cube the field is
\[ \vec{E} = -34\hat{k} \text{ N} / \text{C}, \] and on the bottom face it is \[ \vec{E} = +20\hat{k} \text{ N} / \text{C}. \] Determine the net charge contained within the cube.

7 A point charge of 1.8 \( \mu \text{C} \) is at the center of a Gaussian cube 55 cm on edge. What is the net electric flux through the surface?

Answer:

\[ 2.0 \times 10^5 \text{ N} \cdot \text{m}^2/\text{C} \]

8 When a shower is turned on in a closed bathroom, the splashing of the water on the bare tub can fill the room's air with negatively charged ions and produce an electric field in the air as great as 1000 N/C. Consider a bathroom with dimensions 2.5 m \( \times \) 3.0 m \( \times \) 2.0 m. Along the ceiling, floor, and four walls, approximate the electric field in the air as being directed perpendicular to the surface and as having a uniform magnitude of 600 N/C. Also, treat those surfaces as forming a closed Gaussian surface around the room's air. What are (a) the volume charge density \( \rho \) and (b) the number of excess elementary charges \( e \) per cubic meter in the room's air?

9 Fig. 23-27 shows a Gaussian surface in the shape of a cube with edge length 1.40 m. What are (a) the net flux \( \Phi \) through the surface and (b) the net charge \( q_{\text{enc}} \) enclosed by the surface if

\[ \vec{E} = (3.00y\hat{j}) \text{ N} / \text{C}, \] with \( y \) in meters? What are (c) \( \Phi \) and (d) \( q_{\text{enc}} \) if

\[ \vec{E} = [-4.00\hat{i} + (6.00 + 3.00y)\hat{j}] \text{ N} / \text{C}, \]

Answer:

(a) 8.23 N \cdot m^2/C; (b) 72.9 pC; (c) 8.23 N \cdot m^2/C; (d) 72.9 pC

10 Figure 23-30 shows a closed Gaussian surface in the shape of a cube of edge length 2.00 m. It lies in a region where the nonuniform electric field is given by

\[ \vec{E} = (3.00x + 4.00)\hat{i} + 6.00\hat{j} + 7.00\hat{k} \text{ N} / \text{C}, \] with \( x \) in meters. What is the net charge contained by the cube?

![Figure 23-30](image)

11 Figure 23-31 shows a closed Gaussian surface in the shape of a cube of edge length 2.00 m, with one corner at \( x_1 = 5.00 \text{ m}, y_1 = 4.00 \text{ m} \). The cube lies in a region where the electric field vector is given by

\[ \vec{E} = -3.00\hat{i} - 4.00y^2\hat{j} + 3.00\hat{k} \text{ N} / \text{C}, \] with \( y \) in meters. What is the net charge contained by the cube?
Answer:

-1.70 nC

Figure 23-32 shows two non-conducting spherical shells fixed in place. Shell 1 has uniform surface charge density $+6.0 \, \mu C/m^2$ on its outer surface and radius 3.0 cm; shell 2 has uniform surface charge density $+4.0 \, \mu C/m^2$ on its outer surface and radius 2.0 cm; the shell centers are separated by $L = 10$ cm. In unit-vector notation, what is the net electric field at $x = 2.0$ cm?

Figure 23-32

Problem 12.

**13 SSM** The electric field in a certain region of Earth's atmosphere is directed vertically down. At an altitude of 300 m the field has magnitude 60.0 N/C; at an altitude of 200 m, the magnitude is 100 N/C. Find the net amount of charge contained in a cube 100 m on edge, with horizontal faces at altitudes of 200 and 300 m.

Answer:

3.54 \mu C

**14 Flux and nonconducting shells.** A charged particle is suspended at the center of two concentric spherical shells that are very thin and made of nonconducting material. Figure 23-33a shows a cross section. Figure 23-33b gives the net flux $\Phi$ through a Gaussian sphere centered on the particle, as a function of the radius $r$ of the sphere. The scale of the vertical axis is set by $\Phi_s = 5.0 \times 10^5$ N $\cdot$ m$^2$/C. (a) What is the charge of the central particle? What are the net charges of (b) shell A and (c) shell B?
Problem 14.

A particle of charge \(+q\) is placed at one corner of a Gaussian cube. What multiple of \(q/\varepsilon_0\) gives the flux through (a) each cube face forming that corner and (b) each of the other cube faces?

Answer:

(a) 0; (b) 0.0417

Problem 16.

The box-like Gaussian surface shown in Fig. 23-34 encloses a net charge of \(+24.0\varepsilon_0\) C and lies in an electric field given by \(\vec{E} = [(10.0 + 2.00x)\hat{i} - 3.00\hat{j} + b\hat{k}] \text{ N/C}\), with \(x\) and \(z\) in meters and \(b\) a constant. The bottom face is in the \(xz\) plane; the top face is in the horizontal plane passing through \(y_2 = 1.00\) m. For \(x_1 = 1.00\) m, \(x_2 = 4.00\) m, \(z_1 = 1.00\) m, and \(z_2 = 3.00\) m, what is \(b\)?

sec. 23-6 A Charged Isolated Conductor

Problem 17. SSM A uniformly charged conducting sphere of 1.2 m diameter has a surface charge density of \(8.1 \mu \text{C/m}^2\). (a) Find the net charge on the sphere. (b) What is the total electric flux leaving the surface of the sphere?

Answer:

(a) \(37 \mu \text{C}\); (b) \(4.1 \times 10^6 \text{ N} \cdot \text{m}^2/\text{C}\)

Problem 18. The electric field just above the surface of the charged conducting drum of a photocopying machine has a magnitude \(E\) of \(2.3 \times 10^5\) N/C. What is the surface charge density on the drum?

Problem 19. Space vehicles traveling through Earth's radiation belts can intercept a significant number of electrons. The resulting charge buildup can damage electronic components and disrupt operations.
Suppose a spherical metal satellite 1.3 m in diameter accumulates 2.4 $\mu$C of charge in one orbital revolution. (a) Find the resulting surface charge density. (b) Calculate the magnitude of the electric field just outside the surface of the satellite, due to the surface charge.

**Answer:**

(a) $4.5 \times 10^{-7}$ C/m$^2$; (b) $5.1 \times 10^4$ N/C

**Flux and Conducting Shells.** A charged particle is held at the center of two concentric conducting spherical shells. Figure 23-35a shows a cross section. Figure 23-35b gives the net flux $\Phi$ through a Gaussian sphere centered on the particle, as a function of the radius $r$ of the sphere. The scale of the vertical axis is set by $\Phi_s = 5.0 \times 10^5$ N $\cdot$ m$^2$/C. What are (a) the charge of the central particle and the net charges of (b) shell A and (c) shell B?

![Diagram](image)

**Figure 23-35** Problem 20.

**An isolated conductor has net charge $+10 \times 10^{-6}$ C and a cavity with a point charge $q = +3.0 \times 10^{-6}$ C. What is the charge on (a) the cavity wall and (b) the outer surface?**

**Answer:**

(a) $-3.0 \times 10^{-6}$ C; (b) $+1.3 \times 10^{-5}$ C

**sec. 23-7 Applying Gauss’ Law: Cylindrical Symmetry**

**An electron is released 9.0 cm from a very long nonconducting rod with a uniform 6.0 $\mu$C/m. What is the magnitude of the electron’s initial acceleration?**

**Answer:**

(a) 0.32 $\mu$C; (b) 0.14 $\mu$C

**Figure 23-36 shows a section of a long, thin-walled metal tube of radius $R = 3.00$ cm, with a charge per unit length of $\lambda = 2.00 \times 10^8$ C/m. What is the magnitude $E$ of the electric field at radial distance (a) $r = R/2.00$ and (b) $r = 2.00R$? (c) Graph $E$ versus $r$ for the range $r = 0$ to 2.00$R$.**
25. SSM An infinite line of charge produces a field of magnitude $4.5 \times 10^4$ N/C at distance 2.0 m. Find the linear charge density.

Answer:

$5.0 \, \mu C/m$

26. Figure 23-37a shows a narrow charged solid cylinder that is coaxial with a larger charged cylindrical shell. Both are nonconducting and thin and have uniform surface charge densities on their outer surfaces. Figure 23-37b gives the radial component $E$ of the electric field versus radial distance $r$ from the common axis, and $E_r = 3.0 \times 10^3$ N/C. What is the shell's linear charge density?

27. A long, straight wire has fixed negative charge with a linear charge density of magnitude 3.6 nC/m. The wire is to be enclosed by a coaxial, thin-walled nonconducting cylindrical shell of radius 1.5 cm. The shell is to have positive charge on its outside surface with a surface charge density $\sigma$ that makes the net external electric field zero. Calculate $\sigma$.

Answer:

$3.8 \times 10^{-8}$ C/m$^2$

28. A charge of uniform linear density 2.0 nC/m is distributed along a long, thin, nonconducting rod. The rod is coaxial with a long conducting cylindrical shell (inner radius = 5.0 cm, outer radius = 10 cm). The net charge on the shell is zero. (a) What is the magnitude of the electric field 15 cm from the axis of the shell? What is the surface charge density on the (b) inner and (c) outer surface of the shell?
**29 SSM WWW** Figure 23-38 is a section of a conducting rod of radius \( R_1 = 1.30 \text{ mm} \) and length \( L = 11.00 \text{ m} \) inside a thin-walled coaxial conducting cylindrical shell of radius \( R_2 = 10.0R_1 \) and the (same) length \( L \). The net charge on the rod is \( Q_1 = +3.40 \times 10^{-12} \text{ C} \); that on the shell is \( Q_2 = 2.00Q_1 \). What are the (a) magnitude \( E \) and (b) direction (radially inward or outward) of the electric field at radial distance \( r = 2.00R_2 \)? What are (c) \( E \) and (d) the direction at \( r = 5.00R_1 \)? What is the charge on the (e) interior and (f) exterior surface of the shell?

![Figure 23-38 Problem 29.](image)

**Answer:**

(a) 0.214 N/C; (b) inward; (c) 0.855 N/C; (d) outward; (e) \(-3.40 \times 10^{-12} \text{ C}\); (f) \(-3.40 \times 10^{-12} \text{ C}\)

**30** In Fig. 23-39, short sections of two very long parallel lines of charge are shown, fixed in place, separated by \( L = 8.0 \text{ cm} \). The uniform linear charge densities are \( +6.0 \mu\text{C/m} \) for line 1 and \( -2.0 \mu\text{C/m} \) for line 2. Where along the \( x \) axis shown is the net electric field from the two lines zero?

![Figure 23-39 Problem 30.](image)

**Answer:**

Two long, charged, thin-walled, concentric cylindrical shells have radii of 3.0 and 6.0 cm. The charge per unit length is \( 5.0 \times 10^{-6} \text{ C/m} \) on the inner shell and \( -7.0 \times 10^{-6} \text{ C/m} \) on the outer shell. What are the (a) magnitude \( E \) and (b) direction (radially inward or outward) of the electric field at radial distance \( r = 4.0 \text{ cm} \)? What are (c) \( E \) and (d) the direction at \( r = 8.0 \text{ cm} \)?

**Answer:**

(a) \( 2.3 \times 10^6 \text{ N/C} \); (b) outward; (c) \( 4.5 \times 10^5 \text{ N/C} \); (d) inward

**32** A long, nonconducting, solid cylinder of radius 4.0 cm has a nonuniform volume charge density \( \rho \) that is a function of radial distance \( r \) from the cylinder axis: \( \rho = Ar^2 \). For \( A = 2.5 \text{ \mu C/m}^3 \), what is the magnitude of the electric field at (a) \( r = 3.0 \text{ cm} \) and (b) \( r = 5.0 \text{ cm} \)?
sec. 23-8 Applying Gauss' Law: Planar Symmetry

33 In Fig. 23-40, two large, thin metal plates are parallel and close to each other. On their inner faces, the plates have excess surface charge densities of opposite signs and magnitude $7.00 \times 10^{-22}$ C/m$^2$. In unit-vector notation, what is the electric field at points (a) to the left of the plates, (b) to the right of them, and (c) between them?

![Figure 23-40](image)

**Answer:**

(a) 0; (b) 0; (c) $-7.91 \times 10^{-11}$

34 In Fig. 23-41, a small circular hole of radius $R = 1.80$ cm has been cut in the middle of an infinite, flat, nonconducting surface that has uniform charge density $\sigma = 4.50$ pC/m$^2$. A $z$ axis, with its origin at the hole's center, is perpendicular to the surface. In unit-vector notation, what is the electric field at point $P$ at $z = 2.56$ cm? (Hint: See Eq. 22-26 and use superposition.)

![Figure 23-41](image)

35 Figure 23-42a shows three plastic sheets that are large, parallel, and uniformly charged. Figure 23-42b gives the component of the net electric field along an $x$ axis through the sheets. The scale of the vertical axis is set by $E_x = 6.0 \times 10^5$ N/C. What is the ratio of the charge density on sheet 3 to that on sheet 2?
Problem 35.

Answer:

-1.5

Figure 23-43 shows cross sections through two large, parallel, non-conducting sheets with identical distributions of positive charge with surface charge density $\sigma = 1.77 \times 10^{-22} \text{ C/m}^2$. In unit-vector notation, what is $\vec{E}$ at points (a) above the sheets, (b) between them, and (c) below them?

Problem 36.

Answer:

(a) $5.3 \times 10^7 \text{ N/C}$; (b) 60 N/C

In Fig. 23-44a, an electron is shot directly away from a uniformly charged plastic sheet, at speed $v_s = 2.0 \times 10^5 \text{ m/s}$. The sheet is nonconducting, flat, and very large. Figure 23-44b gives the electron's vertical velocity component $v$ versus time $t$ until the return to the launch point. What is the sheet's surface charge density?
Problem 38.

Figure 23-44 Problem 38.

Figure 23-45 Problem 39.

Answer:

5.0 nC/m^2

Problem 40.

Figure 23-46 Problem 40.
**Problem 41**

An electron is shot directly toward the center of a large metal plate that has surface charge density $-2.0 \times 10^{-6} \text{ C/m}^2$. If the initial kinetic energy of the electron is $1.60 \times 10^{-17} \text{ J}$ and if the electron is to stop (due to electrostatic repulsion from the plate) just as it reaches the plate, how far from the plate must the launch point be?

**Answer:**

0.44 mm

**Problem 42**

Two large metal plates of area 1.0 m$^2$ face each other, 5.0 cm apart, with equal charge magnitudes $|q|$ but opposite signs. The field magnitude $E$ between them (neglect fringing) is 55 N/C. Find $|q|$.

**Problem 43**

Figure 23-47 shows a cross section through a very large nonconducting slab of thickness $d = 9.40$ mm and uniform volume charge density $\rho = 5.80 \text{ fC/m}^3$. The origin of an $x$ axis is at the slab's center. What is the magnitude of the slab's electric field at an $x$ coordinate of (a) 0, (b) 2.00 mm, (c) 4.70 mm, and (d) 26.0 mm?

![Figure 23-47](image)

**Answer:**

(a) 0; (b) 1.31 $\mu$N/C; (c) 3.08 $\mu$N/C; (d) 3.08 $\mu$N/C

**sec. 23-9 Applying Gauss’ Law: Spherical Symmetry**

**Problem 44**

Figure 23-48 gives the magnitude of the electric field inside and outside a sphere with a positive charge distributed uniformly throughout its volume. The scale of the vertical axis is set by $E_s = 5.0 \times 10^7 \text{ N/C}$. What is the charge on the sphere?

![Figure 23-48](image)

**Problem 45**

Two charged concentric spherical shells have radii 10.0 cm and 15.0 cm. The charge on the inner shell is $4.00 \times 10^{-8} \text{ C}$, and that on the outer shell is $2.00 \times 10^{-8} \text{ C}$. Find the electric field (a) at $r = 12.0 \text{ cm}$ and (b) at $r = 20.0 \text{ cm}$.

**Answer:**

(a) $2.50 \times 10^4 \text{ N/C}$; (b) $1.35 \times 10^4 \text{ N/C}$
**46** A point charge causes an electric flux of \(-750 \text{ N} \cdot \text{m}^2/\text{C}\) to pass through a spherical Gaussian surface of 10.0 cm radius centered on the charge. (a) If the radius of the Gaussian surface were doubled, how much flux would pass through the surface? (b) What is the value of the point charge?

**47 SSM** An unknown charge sits on a conducting solid sphere of radius 10 cm. If the electric field 15 cm from the center of the sphere has the magnitude \(3.0 \times 10^3\) N/C and is directed radially inward, what is the net charge on the sphere?

**Answer:**

\(-7.5 \text{ nC}\)

**48** A charged particle is held at the center of a spherical shell. Figure 23-49 gives the magnitude \(E\) of the electric field versus radial distance \(r\). The scale of the vertical axis is set by \(E_s = 10.0 \times 10^7\) N/C. Approximately, what is the net charge on the shell?

![Figure 23-49](image)

**49** In Fig. 23-50, a solid sphere of radius \(a = 2.00\) cm is concentric with a spherical conducting shell of inner radius \(b = 2.00a\) and outer radius \(c = 2.40a\). The sphere has a net uniform charge \(q_1 = +5.00\) fC; the shell has a net charge \(q_2 = -q_1\). What is the magnitude of the electric field at radial distances (a) \(r = 0\), (b) \(r = a/2.00\), (c) \(r = a\), (d) \(r = 1.50a\), (e) \(r = 2.30a\), and (f) \(r = 3.50a\)? What is the net charge on the (g) inner and (h) outer surface of the shell?

![Figure 23-50](image)
Answer:

(a) 0; (b) 56.2 mN/C; (c) 112 mN/C; (d) 49.9 mN/C; (e) 0; (f) 0; (g) -5.00 fC; (h) 0

Figure 23-51 shows two nonconducting spherical shells fixed in place on an x axis. Shell 1 has uniform surface charge density $+4.0 \mu C/m^2$ on its outer surface and radius 0.50 cm, and shell 2 has uniform surface charge density $-2.0 \mu C/m^2$ on its outer surface and radius 2.0 cm; the centers are separated by $L = 6.0$ cm. Other than at $x = \infty$, where on the x axis is the net electric field equal to zero?

Figure 23-51

Problem 50.

In Fig. 23-52, a nonconducting spherical shell of inner radius $a = 2.00$ cm and outer radius $b = 2.40$ cm has (within its thickness) a positive volume charge density $\rho = A/r$, where $A$ is a constant and $r$ is the distance from the center of the shell. In addition, a small ball of charge $q = 45.0$ fC is located at that center. What value should $A$ have if the electric field in the shell ($a \leq r \leq b$) is to be uniform?

Figure 23-52

Problem 51.

Answer:

$1.79 \times 10^{-11}$ C/m$^2$

Figure 23-53 shows a spherical shell with uniform volume charge density $\rho = 1.84$ nC/m$^3$, inner radius $a = 10.0$ cm, and outer radius $b = 2.00a$. What is the magnitude of the electric field at radial distances (a) $r = 0$; (b) $r = a/2.00$, (c) $r = a$, (d) $r = 1.50a$, (e) $r = b$, and (f) $r = 3.00b$?
Problem 52.

The volume charge density of a solid nonconducting sphere of radius \( R = 5.60 \text{ cm} \) varies with radial distance \( r \) as given by \( \rho = (14.1 \text{ pC/m}^3)r/R \). (a) What is the sphere’s total charge? What is the field magnitude \( E \) at (b) \( r = 0 \), (c) \( r = R/2.00 \), and (d) \( r = R \)? (e) Graph \( E \) versus \( r \).

Answer:

(a) 7.78 fC; (b) 0; (c) 5.58 mN/C; (d) 22.3 mN/C

Problem 54.

Figure 23-54 shows, in cross section, two solid spheres with uniformly distributed charge throughout their volumes. Each has radius \( R \). Point \( P \) lies on a line connecting the centers of the spheres, at radial distance \( R/2.00 \) from the center of sphere 1. If the net electric field at point \( P \) is zero, what is the ratio \( q_2/q_1 \) of the total charges?

![Figure 23-54 Problem 54.](image)

Problem 55.

A charge distribution that is spherically symmetric but not uniform radially produces an electric field of magnitude \( E = Kr^4 \), directed radially outward from the center of the sphere. Here \( r \) is the radial distance from that center, and \( K \) is a constant. What is the volume density \( \rho \) of the charge distribution?

Answer:

\[ 6K\varepsilon_0 r^3 \]

Additional Problems

Problem 56.

The electric field in a particular space is \( \vec{E} = (x + 2)\hat{i} \text{ N/C} \) with \( x \) in meters. Consider a cylindrical Gaussian surface of radius 20 cm that is coaxial with the \( x \) axis. One end of the cylinder is at \( x = 0 \). (a) What is the magnitude of the electric flux through the other end of the cylinder at \( x = 2.0 \text{ m} \)? (b) What net charge is enclosed within the cylinder?

Problem 57.

A thin-walled metal spherical shell has radius 25.0 cm and charge \( 2.00 \times 10^{-7} \text{ C} \). Find \( E \) for a point (a) inside the shell, (b) just outside it, and (c) 3.00 m from the center.
A uniform surface charge of density $8.0 \text{nC/m}^2$ is distributed over the entire $xy$ plane. What is the electric flux through a spherical Gaussian surface centered on the origin and having a radius of 5.0 cm?

**Answer:**
(a) $0$; (b) $2.88 \times 10^4 \text{ N/C}$; (c) $200 \text{ N/C}$

Charge of uniform volume density $\rho = 1.2 \text{nC/m}^3$ fills an infinite slab between $x = -5.0 \text{ cm}$ and $x = +5.0 \text{ cm}$. What is the magnitude of the electric field at any point with the coordinate (a) $x = 4.0 \text{ cm}$ and (b) $x = 6.0 \text{ cm}$?

**Answer:**
(a) $5.4 \text{ N/C}$; (b) $6.8 \text{ N/C}$

---

**The chocolate crumb mystery.** Explosions ignited by electrostatic discharges (sparks) constitute a serious danger in facilities handling grain or powder. Such an explosion occurred in chocolate crumb powder at a biscuit factory in the 1970s. Workers usually emptied newly delivered sacks of the powder into a loading bin, from which it was blown through electrically grounded plastic pipes to a silo for storage. Somewhere along this route, two conditions for an explosion were met: (1) The magnitude of an electric field became $3.0 \times 10^6 \text{ N/C}$ or greater, so that electrical breakdown and thus sparking could occur. (2) The energy of a spark was $150 \text{ mJ}$ or greater so that it could ignite the powder explosively. Let us check for the first condition in the powder flow through the plastic pipes.

Suppose a stream of negatively charged powder was blown through a cylindrical pipe of radius $R = 5.0 \text{ cm}$. Assume that the powder and its charge were spread uniformly through the pipe with a volume charge density $\rho$. (a) Using Gauss' law, find an expression for the magnitude of the electric field $\vec{E}$ in the pipe as a function of radial distance $r$ from the pipe center. (b) Does $E$ increase or decrease with increasing $r$? (c) Is $\vec{E}$ directed radially inward or outward? (d) For $\rho = 1.1 \times 10^{-3} \text{ C/m}^3$ (a typical value at the factory), find the maximum $E$ and determine where that maximum field occurs. (e) Could sparking occur, and if so, where? (The story continues with Problem 70 in Chapter 24.)

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A thin-walled metal spherical shell of radius $a$ has a charge $q_a$. Concentric with it is a thin-walled metal spherical shell of radius $b > a$ and charge $q_b$. Find the electric field at points a distance $r$ from the common center, where (a) $r < a$, (b) $a < r < b$, and (c) $r > b$. (d) Discuss the criterion you would use to determine how the charges are distributed on the inner and outer surfaces of the shells.

**Answer:**
(a) $0$; (b) $q_a/4\pi\epsilon_0 r^2$; (c) $(q_a + q_b)/4\pi\epsilon_0 r^2$

---

A point charge $q = 1.0 \times 10^{-7} \text{ C}$ is at the center of a spherical cavity of radius 3.0 cm in a chunk of metal. Find the electric field (a) 1.5 cm from the cavity center and (b) anyplace in the metal.

**Answer:**

---

A proton at speed $v = 3.00 \times 10^5 \text{ m/s}$ orbits at radius $r = 1.00 \text{ cm}$ outside a charged sphere. Find the sphere's charge.

**Answer:**
1.04 nC

Equation 23-11 \( (E = \sigma /\varepsilon_0) \) gives the electric field at points near a charged conducting surface. Apply this equation to a conducting sphere of radius \( r \) and charge \( q \), and show that the electric field outside the sphere is the same as the field of a point charge located at the center of the sphere.

Charge \( Q \) is uniformly distributed in a sphere of radius \( R \). (a) What fraction of the charge is contained within the radius \( r = R/2.00 \)? (b) What is the ratio of the electric field magnitude at \( r = R/2.00 \) to that on the surface of the sphere?

Answer:

(a) 0.125; (b) 0.500

Assume that a ball of charged particles has a uniformly distributed negative charge density except for a narrow radial tunnel through its center, from the surface on one side to the surface on the opposite side. Also assume that we can position a proton anywhere along the tunnel or outside the ball. Let \( F_R \) be the magnitude of the electrostatic force on the proton when it is located at the ball’s surface, at radius \( R \). As a multiple of \( R \), how far from the surface is there a point where the force magnitude is 0.50 \( F_R \)? If we move the proton (a) away from the ball and (b) into the tunnel?

The electric field at point \( P \) just outside the outer surface of a hollow spherical conductor of inner radius 10 cm and outer radius 20 cm has magnitude 450 N/C and is directed outward. When an unknown point charge \( Q \) is introduced into the center of the sphere, the electric field at \( P \) is still directed outward but is now 180 N/C. (a) What was the net charge enclosed by the outer surface before \( Q \) was introduced? (b) What is charge \( Q \)? After \( Q \) is introduced, what is the charge on the (c) inner and (d) outer surface of the conductor?

Answer:

(a) +2.0 nC; (b) -1.2 nC; (c) +1.2 nC; (d) +0.80 nC

The net electric flux through each face of a die (singular of dice) has a magnitude in units of \( 10^3 \) N · m²/C that is exactly equal to the number of spots \( N \) on the face (1 through 6). The flux is inward for \( N \) odd and outward for \( N \) even. What is the net charge inside the die?

Figure 23-55 shows, in cross section, three infinitely large nonconducting sheets on which charge is uniformly spread. The surface charge densities are \( \sigma_1 = +2.00 \mu \text{C/m}^2 \), \( \sigma_2 = +4.00 \mu \text{C/m}^2 \), and \( \sigma_3 = -5.00 \mu \text{C/m}^2 \), and distance \( L = 1.50 \text{ cm} \). In unit-vector notation, what is the net electric field at point \( P \)?

Figure 23-55 Problem 69.
Answer:

\[ \left( 5.65 \times 10^4 \text{ N/C} \right) \]

70 Charge of uniform volume density \( \rho = 3.2 \mu \text{C/m}^3 \) fills a nonconducting solid sphere of radius 5.0 cm. What is the magnitude of the electric field (a) 3.5 cm and (b) 8.0 cm from the sphere's center?

71 A Gaussian surface in the form of a hemisphere of radius \( R = 5.68 \text{ cm} \) lies in a uniform electric field of magnitude \( E = 2.50 \text{ N/C} \). The surface encloses no net charge. At the (flat) base of the surface, the field is perpendicular to the surface and directed into the surface. What is the flux through (a) the base and (b) the curved portion of the surface?

Answer:

(a) \(-2.53 \times 10^{-2} \text{ N} \cdot \text{m}^2/\text{C} \); (b) \(+2.53 \times 10^{-2} \text{ N} \cdot \text{m}^2/\text{C} \)

72 What net charge is enclosed by the Gaussian cube of Problem 2?

73 A nonconducting solid sphere has a uniform volume charge density \( \rho \). Let \( \mathbf{r} \) be the vector from the center of the sphere to a general point \( P \) within the sphere. (a) Show that the electric field at \( P \) is given by \( \mathbf{E} = \frac{\rho}{3} \mathbf{r} \). (Note that the result is independent of the radius of the sphere.) (b) A spherical cavity is hollowed out of the sphere, as shown in Fig. 23-56. Using superposition concepts, show that the electric field at all points within the cavity is uniform and equal to \( \mathbf{E} = \frac{\rho}{3} \mathbf{a} \), where \( \mathbf{a} \) is the position vector from the center of the sphere to the center of the cavity.

Figure 23-56 Problem 73.

74 A uniform charge density of 500 nC/m\(^3\) is distributed throughout a spherical volume of radius 6.00 cm. Consider a cubical Gaussian surface with its center at the center of the sphere. What is the electric flux through this cubical surface if its edge length is (a) 4.00 cm and (b) 14.0 cm?

75 Figure 23-57 shows a Geiger counter, a device used to detect ionizing radiation, which causes ionization of atoms. A thin, positively charged central wire is surrounded by a concentric, circular, conducting cylindrical shell with an equal negative charge, creating a strong radial electric field. The shell contains a low-pressure inert gas. A particle of radiation entering the device through the shell wall ionizes a few of the gas atoms. The resulting free electrons (e) are drawn to the positive wire. However, the electric field is so intense that, between collisions with gas atoms, the free electrons gain energy sufficient to ionize these atoms also. More free electrons are thereby created, and the process is repeated until the electrons reach the wire. The resulting “avalanche” of electrons is collected by the wire, generating a signal that is used to record the passage of the original particle of radiation. Suppose that the radius of the central wire is 25 \( \mu \text{m} \), the inner radius of the shell 1.4 cm, and the length of the shell 16 cm. If the electric field at the shell's inner wall is \( 2.9 \times 10^4 \text{ N/C} \), what is the total positive charge on the central wire?
Problem 75.

**Answer:**

3.6 nC

Charge is distributed uniformly throughout the volume of an infinitely long solid cylinder of radius \( R \). (a) Show that, at a distance \( r < R \) from the cylinder axis, 

\[
E = \frac{\rho r}{2 \varepsilon_0},
\]

where \( \rho \) is the volume charge density. (b) Write an expression for \( E \) when \( r > R \).

**SSM** A spherical conducting shell has a charge of \(-14 \ \mu C\) on its outer surface and a charged particle in its hollow. If the net charge on the shell is \(-10 \ \mu C\), what is the charge (a) on the inner surface of the shell and (b) of the particle?

**Answer:**

(a) +4.0 \( \mu C \); (b) -4.0 \( \mu C \)

A charge of 6.00 pC is spread uniformly throughout the volume of a sphere of radius \( r = 4.00 \ \text{cm} \). What is the magnitude of the electric field at a radial distance of (a) 6.00 cm and (b) 3.00 cm?

Water in an irrigation ditch of width \( w = 3.22 \ \text{m} \) and depth \( d = 1.04 \ \text{m} \) flows with a speed of 0.207 m/s. The mass flux of the flowing water through an imaginary surface is the product of the water's density (1000 kg/m\(^3\)) and its volume flux through that surface. Find the mass flux through the following imaginary surfaces: (a) a surface of area \( wd \), entirely in the water, perpendicular to the flow; (b) a surface with area \( 3wd/2 \), of which \( wd \) is in the water, perpendicular to the flow; (c) a surface of area \( wd/2 \), entirely in the water, perpendicular to the flow; (d) a surface of area \( wd \), half in the water and half out, perpendicular to the flow; (e) a surface of area \( wd \), entirely in the water, with its normal 34.0° from the direction of flow.

**Answer:**

(a) 693 kg/s; (b) 693 kg/s; (c) 347 kg/s; (d) 347 kg/s; (e) 575 kg/s
80 Charge of uniform surface density 8.00 nC/m² is distributed over an entire xy plane; charge of uniform surface density 3.00 nC/m² is distributed over the parallel plane defined by \( z = 2.00 \) m. Determine the magnitude of the electric field at any point having a \( z \) coordinate of (a) 1.00 m and (b) 3.00 m.

81 A spherical ball of charged particles has a uniform charge density. In terms of the ball's radius \( R \), at what radial distances (a) inside and (b) outside the ball is the magnitude of the ball's electric field equal to \( \frac{1}{4} \) of the maximum magnitude of that field?

Answer:
(a) \( 0.25R \); (b) \( 2.0R \)

82 SSM A free electron is placed between two large, parallel, nonconducting plates that are horizontal and 2.3 cm apart. One plate has a uniform positive charge; the other has an equal amount of uniform negative charge. The force on the electron due to the electric field \( \vec{E} \) between the plates balances the gravitational force on the electron. What are (a) the magnitude of the surface charge density on the plates and (b) the direction (up or down) of \( \vec{E} \)?

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?

Answer:
(a) \( 3.0 \times 10^5 \) C; (b) \( 3.6 \times 10^6 \) J

2 The electric potential difference between the ground and a cloud in a particular thunderstorm is \( 1.2 \times 10^9 \) 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 spherical, with radius \( R = 1.0 \times 10^{-6} \) m. How many electrons would one grain have to pick up to have a potential of -400 V on its surface (taking \( V = 0 \) at infinity)?

Answer:
\( 2.8 \times 10^5 \)

sec. 24-5 Calculating the Potential from the Field
Two large, parallel, conducting plates are 12 cm apart and have charges of equal magnitude and opposite sign on their facing surfaces. An electrostatic force of $3.9 \times 10^{15}$ N acts on an electron 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?

An infinite nonconducting sheet has a surface charge density $\sigma = 0.10 \mu C/m^2$ on one side. How far apart are equipotential surfaces whose potentials differ by 50 V?

Answer:

8.8 mm

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

![Electric field line](image)

Figure 24-29 Problem 6.

The electric field in a region of space has the components $E_y = E_z = 0$ and $E_x = (4.00 \text{ N/C})x$. 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 $V_B - V_A$?

Answer:

-32.0 V

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 $E_{x,\text{max}} = 20.0 \text{ N/C}$. 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?

![Electric field graph](image)

Figure 24-30 Problem 8.

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 $d = 3.56$ cm from the sheet? (b) If the electric
potential $V$ is defined to be zero on the sheet, what is $V$ at $P$?

Answer:

(a) $1.87 \times 10^{-21} \text{ J}$; (b) -11.7 mV

10 Two uniformly charged, infinite, nonconducting planes are parallel to a $yz$ plane and positioned at $x = -50 \text{ cm}$ and $x = +50 \text{ cm}$. The charge densities on the planes are $-50 \text{nC/m}^2$ 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 $x = +80 \text{ cm}$? (Hint: Use Gauss' law.)

Answer:

(a) $-0.268 \text{ mV}$; (b) $-0.681 \text{ mV}$

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)?

Answer:

(a) 3.3 nC; (b) 12 nC/m$^2$

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

![Figure 24-31](https://example.com/figure24-31.png)

Figure 24-31 Problem 14.

15 SSM ILW A spherical drop of water carrying a charge of 30 pC has a potential of 500 V at its surface (with $V = 0$ at infinity). (a) What is the radius of the drop? (b) If two such drops of the same charge and radius combine to form a single spherical drop, what is the potential at the surface of the new drop?

Answer:

(a) 0.54 mm; (b) 790 V
Figure 24-32 shows a rectangular array of charged particles fixed in place, with distance $a = 39.0$ cm and the charges shown as integer multiples of $q_1 = 3.40$ pC and $q_2 = 6.00$ pC. With $V = 0$ at infinity, what is the net electric potential at the rectangle's center? (Hint: Thoughtful examination can reduce the calculation.)

![Figure 24-32](image)

**Problem 16.**

In Fig. 24-33, what is the net electric potential at point $P$ due to the four particles if $V = 0$ at infinity, $q = 5.00$ fC, and $d = 4.00$ cm?

![Figure 24-33](image)

**Problem 17.**

Answer:

0.562 mV

Two charged particles are shown in Fig. 24-34a. Particle 1, with charge $q_1$, is fixed in place at distance $d$. Particle 2, with charge $q_2$, can be moved along the $x$ axis. Figure 24-34b gives the net electric potential $V$ at the origin due to the two particles as a function of the $x$ coordinate of particle 2. The scale of the $x$ axis is set by $x_s = 16.0$ cm. The plot has an asymptote of $V = 5.76 \times 10^{-7}$ V as $x \to \infty$. What is $q_2$ in terms of $e$?

![Figure 24-34](image)

**Problem 18.**

In Fig. 24-35, particles with the charges $q_1 = +5e$ and $q_2 = -15e$ are fixed in place with a separation of $d = 24.0$ cm. With electric potential defined to be $V = 0$ at infinity, what are the finite (a) positive and (b) negative values of $x$ at which the net electric potential on the $x$ axis is
Two particles, of charges \( q_1 \) and \( q_2 \), are separated by distance \( d \) in Fig. 24-35. The net electric field due to the particles is zero at \( x = \frac{d}{4} \). With \( V = 0 \) at infinity, locate (in terms of \( d \)) any point on the \( x \) axis (other than at infinity) at which the electric potential due to the two particles is zero.

**sec. 24-8 Potential Due to an Electric Dipole**

\( \bullet \) 21 [ILW] The ammonia molecule \( \text{NH}_3 \) has a permanent electric dipole moment equal to \( 1.47 \) D, where 1 D = 1 debye unit = \( 3.34 \times 10^{-30} \) C \( \cdot \) m. Calculate the electric potential due to an ammonia molecule at a point 52.0 nm away along the axis of the dipole. (Set \( V = 0 \) at infinity.)

**Answer:**

16.3 \( \mu \)V

\( \bullet \) 22 In Fig. 24-36a, a particle of elementary charge \( +e \) is initially at coordinate \( z = 20 \) nm on the dipole axis (here a \( z \) axis) through an electric dipole, on the positive side of the dipole. (The origin of \( z \) is at the center of the dipole.) The particle is then moved along a circular path around the dipole center until it is at coordinate \( z = -20 \) nm, on the negative side of the dipole axis. Figure 24-36b gives the work \( W_o \) done by the force moving the particle versus the angle \( \theta \) that locates the particle relative to the positive direction of the \( z \) axis. The scale of the vertical axis is set by \( W_{oa} = 4.0 \times 10^{-30} \) J. What is the magnitude of the dipole moment?

**sec. 24-9 Potential Due to a Continuous Charge Distribution**

\( \bullet \) 23 (a) Figure 24-37a shows a nonconducting rod of length \( L = 6.00 \) cm and uniform linear charge density \( \lambda = +3.68 \) pC/m. Assume that the electric potential is defined to be \( V = 0 \) at infinity. What is \( V \) at point \( P \) at distance \( d = 8.00 \) cm along the rod's perpendicular bisector? (b) Figure 24-37b shows an identical rod except that one half is now negatively charged. Both halves have a linear charge density of magnitude 3.68 pC/m. With \( V = 0 \) at infinity, what is \( V \) at \( P \)?
Answer:

(a) 24.3 mV; (b) 0

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 $= 120^\circ$. 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?
Answer:

(a) - 2.30 V; (b) - 1.78 V

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

![Figure 24-40](Problem 26)

Problem 26.

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?

![Figure 24-41](Problem 27)

Problem 27.

Answer:

13 kV

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.

![Figure 24-42](Problems 28, 33, 38, and 40)

Problem 28.

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 \( \theta = 20.0^\circ \).
Figure 24-43

Problem 29.

Answer:

32.4 mV

Figure 24-44

Problem 30.

The smiling face of Fig. 24-44 consists of three items:
1. a thin rod of charge -3.0 \( \mu \)C that forms a full circle of radius 6.0 cm;
2. a second thin rod of charge 2.0 \( \mu \)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 \( 1.28 \times 10^{-21} \) C \( \cdot \) m.

Figure 24-44

Problem 30.

What is the net electric potential at the center?

A plastic disk of radius \( R = 64.0 \) cm is charged on one side with a uniform surface charge density \( \sigma = 7.73 \) fC/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 \( D = 25.9 \) cm from the original center?
A nonuniform linear charge distribution given by \( \lambda = bx \), where \( b \) is a constant, is located along an \( x \) axis from \( x = 0 \) to \( x = 0.20 \) m. If \( b = 20 \) nC/m\(^2\) and \( V = 0 \) at infinity, what is the electric potential at (a) the origin and (b) the point \( y = 0.15 \) m on the \( x \) axis?

**Graphical Part**

![Graphical representation](https://example.com/graph.png)

**Figure 24-45** Problem 31.

---

**Answer:**

47.1 \( \mu \)V

---

The thin plastic rod shown in Fig. 24-42 has length \( L = 12.0 \) cm and a nonuniform linear charge density \( \lambda = cx \), where \( c = 28.9 \) pC/m\(^2\). 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.

**Answer:**

18.6 mV

---

### 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?

**Answer:**

---

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

**Answer:**

\((-12 \text{V/m})\hat{i} + (12 \text{V/m})\hat{j}\)

---

- **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?

**Answer:**

150 N/C

---

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

**Answer:**

150 N/C

---

**38** Figure 24-42 shows a thin plastic rod of length \( L = 13.5 \) cm and uniform charge 43.6 \( \mu \)C. (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 $V_s = 500$ V. In unit-vector notation, what is the electric force on the electron?

![Figure 24-46](Problem 39)

**Answer:**

\[
\left(-4.0 \times 10^{-16} \text{N}\right)\hat{i} + \left(1.6 \times 10^{-16} \text{N}\right)\hat{j}
\]

**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/m$^2$. (a) With $V = 0$ at infinity, find the electric potential at point $P_2$ 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?

**Answer:**

(a) 0.90 J; (b) 4.5 J

**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** 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?
Problem 43.

Answer:

-0.192 pJ

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?

Problem 44.

A particle of charge $q$ is fixed at point $P$, and a second particle of mass $m$ and the same charge $q$ is initially held a distance $r_1$ from $P$. The second particle is then released. Determine its speed when it is a distance $r_2$ from $P$. Let $q = 3.1 \, \mu\text{C}$, $m = 20 \, \text{mg}$, $r_1 = 0.90 \, \text{mm}$, and $r_2 = 2.5 \, \text{mm}$.

Answer:

2.5 km/s

A charge of -9.0 nC is uniformly distributed around a thin plastic ring lying in a $yz$ plane with the ring center at the origin. A -6.0 pC point charge is located on the $x$ axis at $x = 3.0 \, \text{m}$. For a ring radius of 1.5 m, how much work must an external force do on the point charge to move it to the origin?

What is the escape speed for an electron initially at rest on the surface of a sphere with a radius of 1.0 cm and a uniformly distributed charge of $1.6 \times 10^{-15} \, \text{C}$? That is, what initial speed must the electron have in order to reach an infinite distance from the sphere and have zero kinetic energy when it gets there?

Answer:

22 km/s
**48.** A thin, spherical, conducting shell of radius $R$ is mounted on an isolating support and charged to a potential of -125 V. An electron is then fired directly toward the center of the shell, from point $P$ at distance $r$ from the center of the shell ($r \gg R$). What initial speed $v_0$ is needed for the electron to just reach the shell before reversing direction?

**49.** Two electrons are fixed 2.0 cm apart. Another electron is shot from infinity and stops midway between the two. What is its initial speed?

**Answer:**

0.32 km/s

**50.** In Fig. 24-49, how much work must we do to bring a particle, of charge $Q = +16e$ and initially at rest, along the dashed line from infinity to the indicated point near two fixed particles of charges $q_1 = +4e$ and $q_2 = -q_1/2$? Distance $d = 1.40$ cm, $\theta_1 = 43^\circ$, and $\theta_2 = 60^\circ$.

![Figure 24-49](image)

**Figure 24-49** Problem 50.

**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?

![Figure 24-50](image)

**Figure 24-50** Problem 51.

**Answer:**

+6.0 x $10^4$V; (b) -7.8 x $10^5$V; (c) 2.5 J; (d) increase; (e) same; (f) same

**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 $r_i = 0.10$ m. What is the magnitude of the dipole moment?
Problem 52.

Two tiny metal spheres $A$ and $B$, mass $m_A = 5.00$ g and $m_B = 10.0$ g, have equal positive charge $q = 5.00 \mu$C. The spheres are connected by a massless nonconducting string of length $d = 1.00$ 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?

Answer:

(a) 0.225 J; (b) $A 45.0 \text{ m/s}^2$, $B 22.5 \text{ m/s}^2$; (c) $A 7.75 \text{ m/s}$, $B 3.87 \text{ m/s}$

Problem 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?

Problem 55.

An electron is projected with an initial speed of $3.2 \times 10^5 \text{ m/s}$ 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?

Answer:

$1.6 \times 10^{-9} \text{ m}$

Problem 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 $U_x = 5.0 \, \text{J}$. What is the charge of particle 3?

![Diagram](image)

**Problem 56.**

Identical 50 $\mu\text{C}$ charges are fixed on an $x$ axis at $x = \pm 3.0 \, \text{m}$. A particle of charge $q = -15 \, \mu\text{C}$ 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 $\text{J}$ 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?

**Answer:**

(a) 3.0 $\text{J}$; (b) -8.5 $\text{m}$

**Problem 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 $\text{eV}$. (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 $x = 3.0 \, \text{cm}$? What are (e) $F$ and (f) the direction if the proton moves just to the right of $x = 5.0 \, \text{cm}$?

![Diagram](image)

**Problem 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 $\text{km/s}$ at the left plate. (a) Is the particle an electron or a proton? (b) What is its speed just as it reaches plate 2?
Problem 59.

Answer:

(a) proton; (b) 65.3 km/s

**60** In Fig. 24-56a, we move an electron from an infinite distance to a point at distance $R = 8.00$ cm from a tiny charged ball. The move requires work $W = 2.16 \times 10^{-13}$ 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 $R = 8.00$ 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?

![Figure 24-56a](image)

![Figure 24-56b](image)

Problem 60.

Answer:

(a) 12; (b) 2

sec. 24-12 Potential of a Charged Isolated Conductor

**62** Sphere 1 with radius $R_1$ has positive charge $q$. Sphere 2 with radius $2.00R_1$ 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?
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.

Answer:
(a) $-1.8 \times 10^2 \text{ V}$; (b) 2.9 kV; (c) -8.9 kV

A hollow metal sphere has a potential of +400 V with respect to ground (defined to be at $V = 0$) and a charge of $5.0 \times 10^{-9} \text{ C}$. Find the electric potential at the center of the sphere.

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?

Answer:
$2.5 \times 10^{-8} \text{ C}$

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) $r = 0.200 \text{ m}$? 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 $V(r)$.

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?

Answer:
(a) $12 \text{ kN/C}$; (b) 1.8 kV; (c) 5.8 cm

Here are the charges and coordinates of two point charges located in an xy plane: $q_1 = +3.00 \times 10^{-6} \text{ C}$, $x = +3.50 \text{ cm}$, $y = +0.500 \text{ cm}$ and $q_2 = -4.00 \times 10^{-6} \text{ C}$, $x = -2.00 \text{ cm}$, $y = +1.50 \text{ cm}$. How much work must be done to locate these charges at their given positions, starting from infinite separation?

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) $V_B - V_C$ and (c) $V_A - V_B$?

Answer:
(a) 64 N/C; (b) 2.9 V; (c) 0

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.

Answer:

\[ p/2\varepsilon_0 r^3 \]

72 The magnitude \( E \) of an electric field depends on the radial distance \( r \) according to \( E = A/r^4 \), 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 \( \text{MV/m} \)?

Answer:

(a) \( 3.6 \times 10^5 \text{ V} \); (b) no

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 \( q_3 \) and, instead, (b) \( q_1 \) and \( q_2 \)?

[Figure 24-57 Problem 74.]

75 An electric field of approximately 100 \( \text{V/m} \) 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.)

Answer:

\( 6.4 \times 10^8 \text{ V} \)

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?

77 In a Millikan oil-drop experiment (Section 22-8), a uniform electric field of \( 1.92 \times 10^5 \text{ N/C} \) is maintained in the region between two plates separated by 1.50 cm. Find the potential difference between the plates.

Answer:

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

![Diagram of three circular arcs](image)

Figure 24-58 Problem 78.

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?

Answer:

$7.0 \times 10^5 \text{ m/s}$

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.

![Diagram of a ring with a point P](image)

Figure 24-59 Problem 80.

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 $V_s = 8.0 \text{ V}$. 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 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 $x = 7.0 \text{ cm}$)? 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 $x = 5.0 \text{ cm}$?
Problem 81.  

Answer:  
(a) 1.8 cm; (b) $8.4 \times 10^{-5}$ m/s; (c) $2.1 \times 10^{-17}$ N; (d) positive; (e) $1.6 \times 10^{-17}$ N; (f) negative

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 $d_1 = 4.00$ m from particle 1 ($q_1 = -2e$) and distance $d_2 = 2.00$ 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?

Answer:  
(a) $+7.19 \times 10^{-10}$ V; (b) $+2.30 \times 10^{-28}$ J; (c) $+2.43 \times 10^{-29}$ J

Problem 84.  
A solid conducting sphere of radius 3.0 cm has a charge of 30 nC distributed uniformly over its surface. Let $A$ be a point 1.0 cm from the center of the sphere, $S$ be a point on the surface of the sphere, and $B$ be a point 5.0 cm from the center of the sphere. What are the electric potential differences (a) $V_S - V_B$ 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 m.

Answer:  
(a) $+7.19 \times 10^{-10}$ V; (b) $+2.30 \times 10^{-28}$ J; (c) $+2.43 \times 10^{-29}$ J
Answer:

2.30 × 10^{-28} \text{ J}

Figure 24-63 shows a hemisphere with a charge of 4.00 \mu 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 cm. What is the electric potential at point P due to the hemisphere?

\[ \text{Figure 24-63} \text{Problem 86.} \]

87 SSM Three +0.12 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?

Answer:

2.1 days

Two charges \( q = +2.0 \ \mu C \) 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 \( q = +2.0 \ \mu C \) 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?

\[ \text{Figure 24-64} \text{Problem 88.} \]

Initially two electrons are fixed in place with a separation of 2.00 \mu m. How much work must we do to bring a third electron in from infinity to complete an equilateral triangle?

Answer:

2.30 × 10^{-22} \text{ J}

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 \( r_2 \).

Two charged, parallel, flat conducting surfaces are spaced \( d = 1.00 \ \text{cm} \) 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?
Answer:

1.48 \times 10^7 \text{ m/s}

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?

![Figure 24-65](Image)

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 \( V_B - V_A \)?

Answer:

-1.92 MV

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 \( r_2 > r_1 \). 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.)

Answer:

(a) \( \frac{Q}{4\pi \varepsilon_0 r} \); (b) \( \frac{\rho}{3\varepsilon_0} \left( 1.5r_2^2 - 0.50r^2 - r_1^2r^{-1} \right) \); (c) \( \frac{Q}{4\pi} \left( \frac{4}{3} \right) \left( r_2^3 - r_1^3 \right) \); (d) yes

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
\[ V = \frac{1}{4\pi \epsilon_0} \frac{q}{\sqrt{z^2 + R^2}} \]

(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 pJ. 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 \(+2e/3\), and one “down” quark, having charge \(-e/3\). Suppose that the three quarks are equidistant from one another. Take that separation distance to be \(1.32 \times 10^{-15} \text{ m}\) and calculate the electric potential energy of the system of (a) only the two up quarks and (b) all three quarks.

Answer:

(a) 0.484 MeV; (b) 0

102 (a) A proton of kinetic energy 4.80 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 \(d_a\). (b) What is \(d_a/d_p\)?

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 \(q_1/q_2\)?

\[ \text{Figure 24-66} \]

Problem 103.

Answer:

-1.7

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 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 V? (b) How long will it take for the temperature of the sphere to increase by 5.0 K due to the energy deposited by the electrons? The heat capacity of the sphere is 14 J/K.
sec. 25-2 Capacitance

1. The two metal objects in Fig. 25-24 have net charges of +70 pC and -70 pC, which result in a 20 V potential difference between them. (a) What is the capacitance of the system? (b) If the charges are changed to +200 pC and -200 pC, what does the capacitance become? (c) What does the potential difference become?

**Answer:**

(a) 3.5 pF; (b) 3.5 pF; (c) 57 V

2. The capacitor in Fig. 25-25 has a capacitance of 25 μF and is initially uncharged. The battery provides a potential difference of 120 V. After switch S is closed, how much charge will pass through it?

![Figure 25-25](Problem 2)

**Answer:**

(a) 3.5 pF; (b) 3.5 pF; (c) 57 V

sec. 25-3 Calculating the Capacitance

3. **SSM** A parallel-plate capacitor has circular plates of 8.20 cm radius and 1.30 mm separation. (a) Calculate the capacitance. (b) Find the charge for a potential difference of 120 V.

**Answer:**

(a) 144 pF; (b) 17.3 nC

4. The plates of a spherical capacitor have radii 38.0 mm and 40.0 mm. (a) Calculate the capacitance. (b) What must be the plate area of a parallel-plate capacitor with the same plate separation and
What is the capacitance of a drop that results when two mercury spheres, each of radius $R = 2.00$ mm, merge?

**Answer:**

0.280 pF

You have two flat metal plates, each of area $1.00 \, m^2$, with which to construct a parallel-plate capacitor. (a) If the capacitance of the device is to be 1.00 F, what must be the separation between the plates? (b) Could this capacitor actually be constructed?

If an uncharged parallel-plate capacitor (capacitance $C$) is connected to a battery, one plate becomes negatively charged as electrons move to the plate face (area $A$). In Fig. 25-26, the depth $d$ from which the electrons come in the plate in a particular capacitor is plotted against a range of values for the potential difference $V$ of the battery. The density of conduction electrons in the copper plates is $8.49 \times 10^{28}$ electrons/m$^3$. The vertical scale is set by $d_s = 1.00$ pm, and the horizontal scale is set by $V_s = 20.0$ V. What is the ratio $C/A$?

![Diagram](image)

**Figure 25-26** Problem 7.

**Answer:**

$6.79 \times 10^{-4}$ F/m$^2$

**sec. 25-4 Capacitors in Parallel and in Series**

How many 1.00 $\mu$F capacitors must be connected in parallel to store a charge of 1.00 C with a potential of 110 V across the capacitors?

Each of the uncharged capacitors in Fig. 25-27 has a capacitance of 25.0 $\mu$F. A potential difference of $V = 4200$ V is established when the switch is closed. How many coulombs of charge then pass through meter A?

![Diagram](image)

**Figure 25-27** Problem 9.
Answer:

315 mC

10 In Fig. 25-28, find the equivalent capacitance of the combination. Assume that $C_1$ is 10.0 μF, $C_2$ is 5.00 μF, and $C_3$ is 4.00 μF.

![Figure 25-28](Problems 10 and 34.)

11 In Fig. 25-29, find the equivalent capacitance of the combination. Assume that $C_1 = 10.0$ μF, $C_2 = 5.00$ μF, and $C_3 = 4.00$ μF.

![Figure 25-29](Problems 11, 17, and 38.)

Answer:

3.16 μF

12 Two parallel-plate capacitors, 6.0 μF each, are connected in parallel to a 10 V battery. One of the capacitors is then squeezed so that its plate separation is 50.0% of its initial value. Because of the squeezing, (a) how much additional charge is transferred to the capacitors by the battery and (b) what is the increase in the total charge stored on the capacitors?

13 A 100 pF capacitor is charged to a potential difference of 50 V, and the charging battery is disconnected. The capacitor is then connected in parallel with a second (initially uncharged) capacitor. If the potential difference across the first capacitor drops to 35 V, what is the capacitance of this second capacitor?

Answer:

43 pF

14 In Fig. 25-30, the battery has a potential difference of $V = 10.0$ V and the five capacitors each have a capacitance of 10.0 μF. What is the charge on (a) capacitor 1 and (b) capacitor 2?
In Fig. 25-31, a 20.0 V battery is connected across capacitors of capacitances $C_1 = C_6 = 3.00 \mu F$ and $C_3 = C_5 = 2.00C_2 = 2.00C_4 = 4.00 \mu F$. What are (a) the equivalent capacitance $C_{eq}$ of the capacitors and (b) the charge stored by $C_{eq}$? What are (c) $V_1$ and (d) $q_1$ of capacitor 1, (e) $V_2$ and (f) $q_2$ of capacitor 2, and (g) $V_3$ and (h) $q_3$ of capacitor 3?

- **15.60**

**Answer:**

(a) 3.00 $\mu F$; (b) 60.0 $\mu C$; (c) 10.0 V; (d) 30.0 $\mu C$; (e) 10.0 V; (f) 20.0 $\mu C$; (g) 5.00 V; (h) 20.0 $\mu C$

**16.** Plot 1 in Fig. 25-32a gives the charge $q$ that can be stored on capacitor 1 versus the electric potential $V$ set up across it. The vertical scale is set by $q_s = 16.0 \mu C$, and the horizontal scale is set by $V_s = 2.0$ V. Plots 2 and 3 are similar plots for capacitors 2 and 3, respectively. Figure 25-32b shows a circuit with those three capacitors and a 6.0 V battery. What is the charge stored on capacitor 2 in that circuit?

**17.** In Fig. 25-29, a potential difference of $V = 100.0$ V is applied across a capacitor arrangement with capacitances $C_1 = 10.0 \mu F$, $C_2 = 5.00 \mu F$, and $C_3 = 4.00 \mu F$. If capacitor 3 undergoes electrical breakdown so that it becomes equivalent to conducting wire, what is the increase in (a)
the charge on capacitor 1 and (b) the potential difference across capacitor 1?

Answer:
(a) 789 \( \mu \)C; (b) 78.9 V

Figure 25-33 shows a circuit section of four air-filled capacitors that is connected to a larger circuit. The graph below the section shows the electric potential \( V(x) \) as a function of position \( x \) along the lower part of the section, through capacitor 4. Similarly, the graph above the section shows the electric potential \( V(x) \) as a function of position \( x \) along the upper part of the section, through capacitors 1, 2, and 3. Capacitor 3 has a capacitance of 0.80 \( \mu \)F. What are the capacitances of (a) capacitor 1 and (b) capacitor 2?

![Figure 25-33 Problem 18.](image)

In Fig. 25-34, the battery has potential difference \( V = 9.0 \) V, \( C_2 = 3.0 \) \( \mu \)F, \( C_4 = 4.0 \) \( \mu \)F, and all the capacitors are initially uncharged. When switch S is closed, a total charge of 12 \( \mu \)C passes through point a and a total charge of 8.0 \( \mu \)C passes through point b. What are (a) \( C_1 \) and (b) \( C_3 \)?

![Figure 25-34 Problem 19.](image)

Answer:
(a) 4.0 \( \mu \)F; (b) 2.0 \( \mu \)F

Figure 25-35 shows a variable “air gap” capacitor for manual tuning. Alternate plates are connected together; one group of plates is fixed in position, and the other group is capable of rotation. Consider a capacitor of \( n = 8 \) plates of alternating polarity, each plate having area \( A = 1.25 \) cm\(^2\) and separated from adjacent plates by distance \( d = 3.40 \) mm. What is the maximum
capacitance of the device?

Figure 25-35 Problem 20.

**21 SSM WWW** In Fig. 25-36, the capacitances are $C_1 = 1.0 \mu F$ and $C_2 = 3.0 \mu F$, and both capacitors are charged to a potential difference of $V = 100 \text{ V}$ but with opposite polarity as shown. Switches $S_1$ and $S_2$ are now closed. (a) What is now the potential difference between points $a$ and $b$? What now is the charge on capacitor (b) 1 and (c) 2?

![Figure 25-36 Problem 21.]

**Answer:**

(a) $50 \text{ V}$; (b) $5.0 \times 10^{-5} \text{ C}$; (c) $1.5 \times 10^{-4} \text{ C}$

**22** In Fig. 25-37, $V = 10 \text{ V}$, $C_1 = 10 \mu F$, and $C_2 = C_3 = 20 \mu F$. Switch $S$ is first thrown to the left side until capacitor 1 reaches equilibrium. Then the switch is thrown to the right. When equilibrium is again reached, how much charge is on capacitor 1?

![Figure 25-37 Problem 22.]

**23** The capacitors in Fig. 25-38 are initially uncharged. The capacitances are $C_1 = 4.0 \mu F$, $C_2 = 8.0 \mu F$, and $C_3 = 12 \mu F$, and the battery's potential difference is $V = 12 \text{ V}$. When switch $S$ is closed, how many electrons travel through (a) point $a$, (b) point $b$, (c) point $c$, and (d) point $d$? In the figure, do the electrons travel up or down through (e) point $b$ and (f) point $c$?

![Figure 25-38 Problem 23.]
**Answer:**

(a) \(4.5 \times 10^{14}\); (b) \(1.5 \times 10^{14}\); (c) \(3.0 \times 10^{14}\); (d) \(4.5 \times 10^{14}\); (e) up; (f) up

**Problem 24.** Figure 25-39 represents two air-filled cylindrical capacitors connected in series across a battery with potential \(V = 10\) V. Capacitor 1 has an inner plate radius of 5.0 mm, an outer plate radius of 1.5 cm, and a length of 5.0 cm. Capacitor 2 has an inner plate radius of 2.5 mm, an outer plate radius of 1.0 cm, and a length of 9.0 cm. The outer plate of capacitor 2 is a conducting organic membrane that can be stretched, and the capacitor can be inflated to increase the plate separation. If the outer plate radius is increased to 2.5 cm by inflation, (a) how many electrons move through point \(P\) and (b) do they move toward or away from the battery?

![Figure 25-39 Problem 24.](image)

**Problem 25.** In Fig. 25-40, two parallel-plate capacitors (with air between the plates) are connected to a battery. Capacitor 1 has a plate area of 1.5 cm\(^2\) and an electric field (between its plates) of magnitude 2000 V/m. Capacitor 2 has a plate area of 0.70 cm\(^2\) and an electric field of magnitude 1500 V/m. What is the total charge on the two capacitors?

![Figure 25-40 Problem 25.](image)

**Answer:**

3.6 pC

**Problem 26.** Capacitor 3 in Fig. 25-41a is a variable capacitor (its capacitance \(C_3\) can be varied). Figure 25-41b gives the electric potential \(V_1\) across capacitor 1 versus \(C_3\). The horizontal scale is set by \(C_{3s} = 12.0\) \(\mu\)F. Electric potential \(V_1\) approaches an asymptote of 10 V as \(C_3 \rightarrow \infty\). What are (a) the electric potential \(V\) across the battery, (b) \(C_1\), and (c) \(C_2\)?

![Figure 25-41 Problem 26.](image)
Problem 26.

Figure 25-41 Problem 26.

Figure 25-42 shows a 12.0 V battery and four uncharged capacitors of capacitances $C_1 = 1.00 \ \mu F$, $C_2 = 2.00 \ \mu F$, $C_3 = 3.00 \ \mu F$, and $C_4 = 4.00 \ \mu F$. If only switch $S_1$ is closed, what is the charge on (a) capacitor 1, (b) capacitor 2, (c) capacitor 3, and (d) capacitor 4? If both switches are closed, what is the charge on (e) capacitor 1, (f) capacitor 2, (g) capacitor 3, and (h) capacitor 4?

**Answer:**

(a) 9.00 $\mu$C; (b) 16.0 $\mu$C; (c) 9.00 $\mu$C; (d) 16.0 $\mu$C; (e) 8.40 $\mu$C; (f) 16.8 $\mu$C; (g) 10.8 $\mu$C; (h) 14.4 $\mu$C

Problem 27.

Figure 25-42 Problem 27.

Problem 28.

sec. 25-5 Energy Stored in an Electric Field

•29 What capacitance is required to store an energy of 10 kW · h at a potential difference of 1000 V?

**Answer:**

72 F

•30 How much energy is stored in 1.00 m$^3$ of air due to the “fair weather” electric field of magnitude 150 V/m?

•31 SSM A 2.0 $\mu$F capacitor and a 4.0 $\mu$F capacitor are connected in parallel across a 300 V potential difference. Calculate the total energy stored in the capacitors.
A parallel-plate air-filled capacitor having area 40 cm$^2$ and plate spacing 1.0 mm is charged to a potential difference of 600 V. Find (a) the capacitance, (b) the magnitude of the charge on each plate, (c) the stored energy, (d) the electric field between the plates, and (e) the energy density between the plates.

A charged isolated metal sphere of diameter 10 cm has a potential of 8000 V relative to $V = 0$ at infinity. Calculate the energy density in the electric field near the surface of the sphere.

0.27 J

A charged isolated metal sphere of diameter 10 cm has a potential of 8000 V relative to $V = 0$ at infinity. Calculate the energy density in the electric field near the surface of the sphere.

0.11 J/m$^3$

In Fig. 25-28, a potential difference $V = 100$ V is applied across a capacitor arrangement with capacitances $C_1 = 10.0 \, \mu F$, $C_2 = 5.00 \, \mu F$, and $C_3 = 4.00 \, \mu F$. What are (a) charge $q_3$, (b) potential difference $V_3$, and (c) stored energy $U_3$ for capacitor 3, (d) $q_1$, (e) $V_1$, and (f) $U_1$ for capacitor 1, and (g) $q_2$, (h) $V_2$, and (i) $U_2$ for capacitor 2?

Assume that a stationary electron is a point of charge. What is the energy density $u$ of its electric field at radial distances (a) $r = 1.00 \, \mu m$, (b) $r = 1.00 \, mm$, (c) $r = 1.00 \, nm$, and (d) $r = 1.00 \, pm$? (e) What is $u$ in the limit as $r \rightarrow 0$?

As a safety engineer, you must evaluate the practice of storing flammable conducting liquids in nonconducting containers. The company supplying a certain liquid has been using a squat, cylindrical plastic container of radius $r = 0.20$ m and filling it to height $h = 10$ cm, which is not the container's full interior height (Fig. 25-44). Your investigation reveals that during handling at the company, the exterior surface of the container commonly acquires a negative charge density of magnitude $2.0 \, \mu C/m^2$ (approximately uniform). Because the liquid is a conducting material, the charge on the container induces charge separation within the liquid. (a) How much negative charge is induced in the center of the liquid's bulk? (b) Assume the capacitance of the central portion of the liquid relative to ground is 35 pF. What is the potential energy associated with the negative charge in that effective capacitor? (c) If a spark occurs between the ground and the central portion of the liquid (through the venting port), the potential energy can be fed into the spark. The minimum spark energy needed to ignite the liquid is 10 mJ. In this situation, can a spark ignite the liquid?

The parallel plates in a capacitor, with a plate area of 8.50 cm$^2$ and an air-filled separation of 3.00 mm, are charged by a 6.00 V battery. They are then disconnected from the
battery and pulled apart (without discharge) to a separation of 8.00 mm. Neglecting fringing, find
(a) the potential difference between the plates, (b) the initial stored energy, (c) the final stored
energy, and (d) the work required to separate the plates.

Answer:
(a) 16.0 V; (b) 45.1 pJ; (c) 120 pJ; (d) 75.2 pJ

In Fig. 25-29, a potential difference $V = 100$ V is applied across a capacitor arrangement with
capacitances $C_1 = 10.0 \mu F$, $C_2 = 5.00 \mu F$, and $C_3 = 15.0 \mu F$. What are (a) charge $q_3$, (b) potential
difference $V_3$, and (c) stored energy $U_3$ for capacitor 3, (d) $q_1$, (e) $V_1$, and (f) $U_1$ for capacitor 1, and
(g) $q_2$, (h) $V_2$, and (i) $U_2$ for capacitor 2?

In Fig. 25-45, $C_1 = 10.0 \mu F$, $C_2 = 20.0 \mu F$, and $C_3 = 25.0 \mu F$. If no capacitor can withstand a
potential difference of more than 100 V without failure, what are (a) the magnitude of the
maximum potential difference that can exist between points $A$ and $B$ and (b) the maximum energy
that can be stored in the three-capacitor arrangement?

Answer:
(a) 190 V; (b) 95 mJ

sec. 25-6 Capacitor with a Dielectric

An air-filled parallel-plate capacitor has a capacitance of 1.3 pF. The separation of the plates is
doubled, and wax is inserted between them. The new capacitance is 2.6 pF. Find the dielectric
constant of the wax.

A coaxial cable used in a transmission line has an inner radius of 0.10 mm and an outer
radius of 0.60 mm. Calculate the capacitance per meter for the cable. Assume that the space
between the conductors is filled with polystyrene.

Answer:
81 pF/m

A parallel-plate air-filled capacitor has a capacitance of 50 pF. (a) If each of its plates has an area
of 0.35 m$^2$, what is the separation? (b) If the region between the plates is now filled with material
having $\kappa = 5.6$, what is the capacitance?

Given a 7.4 pF air-filled capacitor, you are asked to convert it to a capacitor that can store up to 7.4
mJ with a maximum potential difference of 652 V. Which dielectric in Table 25-1 should you use
to fill the gap in the capacitor if you do not allow for a margin of error?

Answer:
Pyrex

You are asked to construct a capacitor having a capacitance near 1 nF and a breakdown potential
in excess of 10 000 V. You think of using the sides of a tall Pyrex drinking glass as a dielectric,
lining the inside and outside curved surfaces with aluminum foil to act as the plates. The glass is
15 cm tall with an inner radius of 3.6 cm and an outer radius of 3.8 cm. What are the (a) capacitance and (b) breakdown potential of this capacitor?

**45** A certain parallel-plate capacitor is filled with a dielectric for which \( \kappa = 5.5 \). The area of each plate is 0.034 m\(^2\), and the plates are separated by 2.0 mm. The capacitor will fail (short out and burn up) if the electric field between the plates exceeds 200 kN/C. What is the maximum energy that can be stored in the capacitor?

**Answer:**

66 \( \mu \)J

**46** In Fig. 25-46, how much charge is stored on the parallel-plate capacitors by the 12.0 V battery? One is filled with air, and the other is filled with a dielectric for which \( \kappa = 3.00 \); both capacitors have a plate area of \( 5.00 \times 10^{-3} \) m\(^2\) and a plate separation of 2.00 mm.

![Figure 25-46 Problem 46.](image)

**Answer:**

0.63 m\(^2\)

**47** A certain substance has a dielectric constant of 2.8 and a dielectric strength of 18 MV/m. If it is used as the dielectric material in a parallel-plate capacitor, what minimum area should the plates of the capacitor have to obtain a capacitance of \( 7.0 \times 10^{-2} \) \( \mu \)F and to ensure that the capacitor will be able to withstand a potential difference of 4.0 kV?

**Answer:**

0.63 m\(^2\)

**48** Figure 25-47 shows a parallel-plate capacitor with a plate area \( A = 5.56 \) cm\(^2\) and separation \( d = 5.56 \) mm. The left half of the gap is filled with material of dielectric constant \( \kappa_1 = 7.00 \); the right half is filled with material of dielectric constant \( \kappa_2 = 12.0 \). What is the capacitance?

![Figure 25-47 Problem 48.](image)

**Answer:**

17.3 pF

**49** Figure 25-48 shows a parallel-plate capacitor with a plate area \( A = 7.89 \) cm\(^2\) and plate separation \( d = 4.62 \) mm. The top half of the gap is filled with material of dielectric constant \( \kappa_1 = 11.0 \); the bottom half is filled with material of dielectric constant \( \kappa_2 = 12.0 \). What is the capacitance?
**Problem 49.**

Figure 25-49 shows a parallel-plate capacitor of plate area \( A = 10.5 \text{ cm}^2 \) and plate separation \( 2d = 7.12 \text{ mm} \). The left half of the gap is filled with material of dielectric constant \( \kappa_1 = 21.0 \); the top of the right half is filled with material of dielectric constant \( \kappa_2 = 42.0 \); the bottom of the right half is filled with material of dielectric constant \( \kappa_3 = 58.0 \). What is the capacitance?

**Problem 50.**

sec. 25-8 Dielectrics and Gauss' Law

A parallel-plate capacitor has a capacitance of 100 pF, a plate area of 100 cm\(^2\), and a mica dielectric \((\kappa = 5.4)\) completely filling the space between the plates. At 50 V potential difference, calculate (a) the electric field magnitude \( E \) in the mica, (b) the magnitude of the free charge on the plates, and (c) the magnitude of the induced surface charge on the mica.

Answer:

(a) 10 kV/m; (b) 5.0 nC; (c) 4.1 nC

For the arrangement of Fig. 25-17, suppose that the battery remains connected while the dielectric slab is being introduced. Calculate (a) the capacitance, (b) the charge on the capacitor plates, (c) the electric field in the gap, and (d) the electric field in the slab, after the slab is in place.

A parallel-plate capacitor has plates of area 0.12 m\(^2\) and a separation of 1.2 cm. A battery charges the plates to a potential difference of 120 V and is then disconnected. A dielectric slab of thickness 4.0 mm and dielectric constant 4.8 is then placed symmetrically between the plates. (a) What is the capacitance before the slab is inserted? (b) What is the capacitance with the slab in place? What is the free charge \( q \) (c) before and (d) after the slab is inserted? What is the magnitude of the electric field (e) in the space between the plates and dielectric and (f) in the dielectric itself? (g) With the slab in place, what is the potential difference across the plates? (h) How much external work is involved in inserting the slab?

Answer:

(a) 89 pF; (b) 0.12 nF; (c) 11 nC; (d) 11 nC; (e) 10 kV/m; (f) 2.1 kV/m; (g) 88 V; (h) -0.17 \( \mu \)J

Two parallel plates of area 100 cm\(^2\) are given charges of equal magnitudes \( 8.9 \times 10^{-7} \text{ C} \) but opposite signs. The electric field within the dielectric material filling the space between the plates
is $1.4 \times 10^6 \text{ V/m}$. (a) Calculate the dielectric constant of the material. (b) Determine the magnitude of the charge induced on each dielectric surface.

The space between two concentric conducting spherical shells of radii $b = 1.70 \text{ cm}$ and $a = 1.20 \text{ cm}$ is filled with a substance of dielectric constant $\kappa = 23.5$. A potential difference $V = 73.0 \text{ V}$ is applied across the inner and outer shells. Determine (a) the capacitance of the device, (b) the free charge $q$ on the inner shell, and (c) the charge $q'$ induced along the surface of the inner shell.

**Answer:**

(a) 0.107 nF; (b) 7.79 nC; (c) 7.45 nC

**Additional Problems**

56 In Fig. 25-50, the battery potential difference $V$ is 10.0 V and each of the seven capacitors has capacitance 10.0 $\mu$F. What is the charge on (a) capacitor 1 and (b) capacitor 2?

57 SSM In Fig. 25-51, $V = 9.0 \text{ V}$, $C_1 = C_2 = 30 \mu$F, and $C_3 = C_4 = 15 \mu$F. What is the charge on capacitor 4?

**Answer:**

45 $\mu$C

58 The capacitances of the four capacitors shown in Fig. 25-52 are given in terms of a certain quantity $C$. (a) If $C = 50 \mu$F, what is the equivalent capacitance between points $A$ and $B$? (Hint: First imagine that a battery is connected between those two points; then reduce the circuit to an equivalent capacitance.) (b) Repeat for points $A$ and $D$. 
In Fig. 25-53, \( V = 12 \text{ V} \), \( C_1 = C_4 = 2.0 \mu \text{F} \), \( C_2 = 4.0 \mu \text{F} \), and \( C_3 = 1.0 \mu \text{F} \). What is the charge on capacitor 4?

**Answer:**

\( 16 \mu \text{C} \)

---

The chocolate crumb mystery. This story begins with Problem 60 in Chapter 23. As part of the investigation of the biscuit factory explosion, the electric potentials of the workers were measured as they emptied sacks of chocolate crumb powder into the loading bin, stirring up a cloud of the powder around themselves. Each worker had an electric potential of about 7.0 kV relative to the ground, which was taken as zero potential. (a) Assuming that each worker was effectively a capacitor with a typical capacitance of 200 pF, find the energy stored in that effective capacitor. If a single spark between the worker and any conducting object connected to the ground neutralized the worker, that energy would be transferred to the spark. According to measurements, a spark that could ignite a cloud of chocolate crumb powder, and thus set off an explosion, had to have an energy of at least 150 mJ. (b) Could a spark from a worker have set off an explosion in the cloud of powder in the loading bin? (The story continues with Problem 60 in Chapter 26.)

---

Figure 25-54 shows capacitor 1 \( (C_1 = 8.00 \mu \text{F}) \), capacitor 2 \( (C_2 = 6.00 \mu \text{F}) \), and capacitor 3 \( (C_3 = 8.00 \mu \text{F}) \) connected to a 12.0 V battery. When switch S is closed so as to connect uncharged capacitor 4 \( (C_4 = 6.00 \mu \text{F}) \), (a) how much charge passes through point \( P \) from the battery and (b) how much charge shows up on capacitor 4? (c) Explain the discrepancy in those two results.
Answer:
(a) 7.20 μC; (b) 18.0 μC; (c) Battery supplies charges only to plates to which it is connected; charges on other plates are due to electron transfers between plates, in accord with new distribution of voltages across the capacitors. So the battery does not directly supply charge on capacitor 4.

62 Two air-filled, parallel-plate capacitors are to be connected to a 10 V battery, first individually, then in series, and then in parallel. In those arrangements, the energy stored in the capacitors turns out to be, listed least to greatest: 75 μJ, 100 μJ, 300 μJ, and 400 μJ. Of the two capacitors, what is the (a) smaller and (b) greater capacitance?

63 Two parallel-plate capacitors, 6.0 μF each, are connected in series to a 10 V battery. One of the capacitors is then squeezed so that its plate separation is halved. Because of the squeezing, (a) how much additional charge is transferred to the capacitors by the battery and (b) what is the increase in the total charge stored on the capacitors (the charge on the positive plate of one capacitor plus the charge on the positive plate of the other capacitor)?

Answer:
(a) 10 μC; (b) 20 μC

64 In Fig. 25-55, \( V = 12 \) V, \( C_1 = C_5 = C_6 = 6.0 \) μF, and \( C_2 = C_3 = C_4 = 4.0 \) μF. What are (a) the net charge stored on the capacitors and (b) the charge on capacitor 4?

Figure 25-55

65 In Fig. 25-56, the parallel-plate capacitor of plate area \( 2.00 \times 10^{-2} \) m\(^2\) is filled with two dielectric slabs, each with thickness 2.00 mm. One slab has dielectric constant 3.00, and the other, 4.00. How much charge does the 7.00 V battery store on the capacitor?

Figure 25-56

Answer:
1.06 nC

66 A cylindrical capacitor has radii \( a \) and \( b \) as in Fig. 25-6. Show that half the stored electric potential
energy lies within a cylinder whose radius is \( r = \sqrt{ab} \).

67A capacitor of capacitance \( C_1 = 6.00 \, \mu F \) is connected in series with a capacitor of capacitance \( C_2 = 4.00 \, \mu F \), and a potential difference of 200 V is applied across the pair. (a) Calculate the equivalent capacitance. What are (b) charge \( q_1 \) and (c) potential difference \( V_1 \) on capacitor 1 and (d) \( q_2 \) and (e) \( V_2 \) on capacitor 2?

**Answer:**

(a) 2.40 \( \mu F \); (b) 0.480 mC; (c) 80 V; (d) 0.480 mC; (e) 120 V

68Repeat Problem 67 for the same two capacitors but with them now connected in parallel.

69A certain capacitor is charged to a potential difference \( V \). If you wish to increase its stored energy by 10%, by what percentage should you increase \( V \)?

**Answer:**

4.9%

70A slab of copper of thickness \( b = 2.00 \, \text{mm} \) is thrust into a parallel-plate capacitor of plate area \( A = 2.40 \, \text{cm}^2 \) and plate separation \( d = 5.00 \, \text{mm} \), as shown in Fig. 25-57; the slab is exactly halfway between the plates. (a) What is the capacitance after the slab is introduced? (b) If a charge \( q = 3.40 \, \mu C \) is maintained on the plates, what is the ratio of the stored energy before to that after the slab is inserted? (c) How much work is done on the slab as it is inserted? (d) Is the slab sucked in or must it be pushed in?

![Figure 25-57](image_url) Problems 70 and 71.

71Repeat Problem 70, assuming that a potential difference \( V = 85.0 \, \text{V} \), rather than the charge, is held constant.

**Answer:**

(a) 0.708 pF; (b) 0.600; (c) \( 1.02 \times 10^{-9} \) J; (d) sucked in

72A potential difference of 300 V is applied to a series connection of two capacitors of capacitances \( C_1 = 2.00 \, \mu F \) and \( C_2 = 8.00 \, \mu F \). What are (a) charge \( q_1 \) and (b) potential difference \( V_1 \) on capacitor 1 and (c) \( q_2 \) and (d) \( V_2 \) on capacitor 2? The charged capacitors are then disconnected from each other and from the battery. Then the capacitors are reconnected with plates of the same signs wired together (the battery is not used). What now are (e) \( q_1 \), (f) \( V_1 \), (g) \( q_2 \), and (h) \( V_2 \)? Suppose, instead, the capacitors charged in part (a) are reconnected with plates of opposite signs wired together. What now are (i) \( q_1 \), (j) \( V_1 \), (k) \( q_2 \), and (l) \( V_2 \)?

73Figure 25-58 shows a four-capacitor arrangement that is connected to a larger circuit at points \( A \) and \( B \). The capacitances are \( C_1 = 10 \, \mu F \) and \( C_2 = C_3 = C_4 = 20 \, \mu F \). The charge on capacitor 1 is 30 \( \mu C \). What is the magnitude of the potential difference \( V_A - V_B \)?
You have two plates of copper, a sheet of mica (thickness = 0.10 mm, $\kappa = 5.4$), a sheet of glass (thickness = 2.0 mm, $\kappa = 7.0$), and a slab of paraffin (thickness = 1.0 cm, $\kappa = 2.0$). To make a parallel-plate capacitor with the largest $C$, which sheet should you place between the copper plates?

A capacitor of unknown capacitance $C$ is charged to 100 V and connected across an initially uncharged 60 $\mu$F capacitor. If the final potential difference across the 60 $\mu$F capacitor is 40 V, what is $C$?

A 10 V battery is connected to a series of $n$ capacitors, each of capacitance 2.0 $\mu$F. If the total stored energy is 25 $\mu$J, what is $n$?

In Fig. 25-59, two parallel-plate capacitors $A$ and $B$ are connected in parallel across a 600 V battery. Each plate has area 80.0 cm$^2$; the plate separations are 3.00 mm. Capacitor $A$ is filled with air; capacitor $B$ is filled with a dielectric of dielectric constant $\kappa = 2.60$. Find the magnitude of the electric field within (a) the dielectric of capacitor $B$ and (b) the air of capacitor $A$. What are the free charge densities $\sigma$ on the higher-potential plate of (c) capacitor $A$ and (d) capacitor $B$? (e) What is the induced charge density $\sigma'$ on the top surface of the dielectric?

You have many 2.0 $\mu$F capacitors, each capable of withstanding 200 V without undergoing electrical breakdown (in which they conduct charge instead of storing it). How would you assemble a combination having an equivalent capacitance of (a) 0.40 $\mu$F and (b) 1.2 $\mu$F, each combination capable of withstanding 1000 V?
sec. 26-2 Electric Current

•1 During the 4.0 min a 5.0 A current is set up in a wire, how many (a) coulombs and (b) electrons pass through any cross section across the wire's width?

Answer:
(a) 1.2 kC; (b) $7.5 \times 10^{31}$

••2 An isolated conducting sphere has a 10 cm radius. One wire carries a current of 1.000 002 0 A into it. Another wire carries a current of 1.000 000 0 A out of it. How long would it take for the sphere to increase in potential by 1000 V?

••3 A charged belt, 50 cm wide, travels at 30 m/s between a source of charge and a sphere. The belt carries charge into the sphere at a rate corresponding to 100 mA. Compute the surface charge density on the belt.

Answer:
6.7 μC/m²

sec. 26-3 Current Density

•4 The (United States) National Electric Code, which sets maximum safe currents for insulated copper wires of various diameters, is given (in part) in the table. Plot the safe current density as a function of diameter. Which wire gauge has the maximum safe current density? (“Gauge” is a way of identifying wire diameters, and 1 mil = $10^{-3}$ in.)

<table>
<thead>
<tr>
<th>Gauge</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, mils</td>
<td>204</td>
<td>162</td>
<td>129</td>
<td>102</td>
<td>81</td>
<td>64</td>
<td>51</td>
<td>40</td>
</tr>
<tr>
<td>Safe current, A</td>
<td>70</td>
<td>50</td>
<td>35</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

•5 SSM WWW A beam contains $2.0 \times 10^8$ doubly charged positive ions per cubic centimeter, all of which are moving north with a speed of $1.0 \times 10^5$ m/s. What are the (a) magnitude and (b) direction of the current density $\vec{J}$. (c) What additional quantity do you need to calculate the total current $i$ in this ion beam?

Answer:
(a) 6.4 A/m²; (b) north; (c) cross-sectional area

•6 A certain cylindrical wire carries current. We draw a circle of radius $r$ around its central axis in Fig. 26-23a to determine the current $i$ within the circle. Figure 26-23b shows current $i$ as a function of $r^2$. The vertical scale is set by $i_s = 4.0$ mA, and the horizontal scale is set by $r_s^2 = 4.0 \text{ mm}^2$. (a) Is the current density uniform? (b) If so, what is its magnitude?
•7 A fuse in an electric circuit is a wire that is designed to melt, and thereby open the circuit, if the current exceeds a predetermined value. Suppose that the material to be used in a fuse melts when the current density rises to 440 A/cm$^2$. What diameter of cylindrical wire should be used to make a fuse that will limit the current to 0.50 A?

**Answer:**

0.38 mm

•8 A small but measurable current of $1.2 \times 10^{-10}$ A exists in a copper wire whose diameter is 2.5 μm. The number of charge carriers per unit volume is $8.49 \times 10^{28}$ m$^{-3}$. Assuming the current is uniform, calculate the (a) current density and (b) electron drift speed.

**Answer:**

(a) 18.1 μA

•9 The magnitude $J(r)$ of the current density in a certain cylindrical wire is given as a function of radial distance from the center of the wire’s cross section as $J(r) = Br$, where $r$ is in meters, $J$ is in amperes per square meter, and $B = 2.00 \times 10^5$ A/m$^3$. This function applies out to the wire’s radius of 2.00 mm. How much current is contained within the width of a thin ring concentric with the wire if the ring has a radial width of 10.0 μm and is at a radial distance of 1.20 mm?

**Answer:**

18.1 μA

•10 The magnitude $J$ of the current density in a certain lab wire with a circular cross section of radius $R = 2.00$ mm is given by $J = (3.00 \times 10^8)r^2$, with $J$ in amperes per square meter and radial distance $r$ in meters. What is the current through the outer section bounded by $r = 0.900R$ and $r = R$?

•11 What is the current in a wire of radius $R = 3.40$ mm if the magnitude of the current density is given by (a) $J_a = J_0 r/R$ and (b) $J_b = J_0 (1 - r/R)$, in which $r$ is the radial distance and $J_0 = 5.50 \times 10^4$ A/m$^2$? (c) Which function maximizes the current density near the wire’s surface?

**Answer:**

(a) 1.33 A; (b) 0.666 A; (c) $J_a$

•12 Near Earth, the density of protons in the solar wind (a stream of particles from the Sun) is 8.70 cm$^{-3}$, and their speed is 470 km/s. (a) Find the current density of these protons. (b) If Earth’s magnetic field did not deflect the protons, what total current would Earth receive?

**Answer:**

(a) The current density is $8.00 \times 10^{10}$ A/m$^2$.

•13 How long does it take electrons to get from a car battery to the starting motor? Assume the current is 300 A and the electrons travel through a copper wire with cross-sectional area 0.21 cm$^2$ and length 0.85 m. The number of charge carriers per unit volume is $8.49 \times 10^{28}$ m$^{-3}$.

**Answer:**

The time taken is 0.027 μs.
sec. 26-4 Resistance and Resistivity

14 A human being can be electrocuted if a current as small as 50 mA passes near the heart. An electrician working with sweaty hands makes good contact with the two conductors he is holding, one in each hand. If his resistance is 2000 Ω, what might the fatal voltage be?

Answer:

2.4 V

15 A coil is formed by winding 250 turns of insulated 16-gauge copper wire (diameter = 1.3 mm) in a single layer on a cylindrical form of radius 12 cm. What is the resistance of the coil? Neglect the thickness of the insulation. (Use Table 26-1.)

Answer:

2.4 Ω

16 Copper and aluminum are being considered for a high-voltage transmission line that must carry a current of 60.0 A. The resistance per unit length is to be 0.150 Ω/km. The densities of copper and aluminum are 8960 and 2600 kg/m³, respectively. Compute (a) the magnitude J of the current density and (b) the mass per unit length λ for a copper cable and (c) J and (d) λ for an aluminum cable.

Answer:

2.0 × 10⁶ (Ω · m)⁻¹

17 A wire of Nichrome (a nickel–chromium–iron alloy commonly used in heating elements) is 1.0 m long and 1.0 mm² in cross-sectional area. It carries a current of 4.0 A when a 2.0 V potential difference is applied between its ends. Calculate the conductivity σ of Nichrome.

Answer:

2.0 × 10⁶ (Ω · m⁻¹)

18 A wire 4.00 m long and 6.00 mm in diameter has a resistance of 15.0 mΩ. A potential difference of 23.0 V is applied between the ends. (a) What is the current in the wire? (b) What is the magnitude of the current density? (c) Calculate the resistivity of the wire material. (d) Using Table 26-1, identify the material.

Answer:

2.0 × 10⁻⁸ Ω · m

19 What is the resistivity of a wire of 1.0 mm diameter, 2.0 m length, and 50 m resistance?

Answer:

2.0 × 10⁻⁸ Ω · m

20 A certain wire has a resistance R. What is the resistance of a second wire, made of the same material, that is half as long and has half the diameter?

Answer:

(1.8 × 10³)°C

21 Kiting during a storm. The legend that Benjamin Franklin flew a kite as a storm approached is only a legend—he was neither stupid nor suicidal. Suppose a kite string of radius 2.00 mm extends directly upward by 0.800 km and is coated with a 0.500 mm layer of water having resistivity 150 Ω. If the potential difference between the two ends of the string is 160 MV, what is the current through the water layer? The danger is not this current but the chance that the...
string draws a lightning strike, which can have a current as large as 500 000 A (way beyond just being lethal).

• 23 When 115 V is applied across a wire that is 10 m long and has a 0.30 mm radius, the magnitude of the current density is $1.4 \times 10^4 \text{ A/m}^2$. Find the resistivity of the wire.

**Answer:**

$$8.2 \times 10^{-4} \Omega \cdot 	ext{m}$$

• 24 Figure 26-24 gives the magnitude $E(x)$ of the electric fields that have been set up by a battery along a resistive rod of length 9.00 mm (Fig. 26-24b). The vertical scale is set by $E_s = 4.00 \times 10^3 \text{ V/m}$. The rod consists of three sections of the same material but with different radii. (The schematic diagram of Fig. 26-24b does not indicate the different radii.) The radius of section 3 is 2.00 mm. What is the radius of (a) section 1 and (b) section 2?

**Figure 26-24** Problem 24.

• 25 **SSM ILW** A wire with a resistance of 6.0 Ω is drawn out through a die so that its new length is three times its original length. Find the resistance of the longer wire, assuming that the resistivity and density of the material are unchanged.

**Answer:**

54 Ω

• 26 In Fig. 26-25a, a 9.00 V battery is connected to a resistive strip that consists of three sections with the same cross-sectional areas but different conductivities. Figure 26-25b gives the electric potential $V(x)$ versus position $x$ along the strip. The horizontal scale is set by $x_s = 8.00 \text{ mm}$. Section 3 has conductivity $3.00 \times 10^7 \text{ (Ω · m)}^{-1}$. What is the conductivity of section (a) 1 and (b) 2?

**Figure 26-25** Problem 26.

• 27 **SSM WWW** Two conductors are made of the same material and have the same length. Conductor $A$ is a solid wire of diameter 1.0 mm. Conductor $B$ is a hollow tube of outside diameter 2.0 mm and inside diameter 1.0 mm. What is the resistance ratio $R_A/R_B$, measured between their ends?
Answer:

3.0

Figure 26-26 gives the electric potential $V(x)$ along a copper wire carrying uniform current, from a point of higher potential $V_i = 12.0 \mu V$ at $x = 0$ to a point of zero potential at $x_s = 3.00$ m. The wire has a radius of 2.00 mm. What is the current in the wire?

**28**

A potential difference of 3.00 nV is set up across a 2.00 cm length of copper wire that has a radius of 2.00 mm. How much charge drifts through a cross section in 3.00 ms?

**Answer:**

$3.35 \times 10^{-7}$ C

**29** If the gauge number of a wire is increased by 6, the diameter is halved; if a gauge number is increased by 1, the diameter decreases by the factor $2^{1/6}$ (see the table in Problem 4). Knowing this, and knowing that 1000 ft of 10-gauge copper wire has a resistance of approximately 1.00 $\Omega$, estimate the resistance of 25 ft of 22-gauge copper wire.

**30** An electrical cable consists of 125 strands of fine wire, each having 2.65 $\mu \Omega$ resistance. The same potential difference is applied between the ends of all the strands and results in a total current of 0.750 A. (a) What is the current in each strand? (b) What is the applied potential difference? (c) What is the resistance of the cable?

**Answer:**

(a) 6.00 mA; (b) $1.59 \times 10^{-8}$ V; (c) 21.2 n$\Omega$

**31** Earth's lower atmosphere contains negative and positive ions that are produced by radioactive elements in the soil and cosmic rays from space. In a certain region, the atmospheric electric field strength is 120 V/m and the field is directed vertically down. This field causes singly charged positive ions, at a density of 620 cm$^{-3}$, to drift downward and singly charged negative ions, at a density of 550 cm$^{-3}$, to drift upward (Fig. 26-27). The measured conductivity of the air in that region is $2.70 \times 10^{-14}$ $(\Omega \cdot m)^{-1}$. Calculate (a) the magnitude of the current density and (b) the ion drift speed, assumed to be the same for positive and negative ions.
Problem 32.

A block in the shape of a rectangular solid has a cross-sectional area of 3.50 cm$^2$ across its width, a front-to-rear length of 15.8 cm, and a resistance of 935 Ω. The block's material contains $5.33 \times 10^{22}$ conduction electrons/m$^3$. A potential difference of 35.8 V is maintained between its front and rear faces. (a) What is the current in the block? (b) If the current density is uniform, what is its magnitude? What are (c) the drift velocity of the conduction electrons and (d) the magnitude of the electric field in the block?

Answer:

(a) 38.3 mA; (b) 109 A/m$^2$; (c) 1.28 cm/s; (d) 227 V/m

Problem 34.

Figure 26-28 shows wire section 1 of diameter $D_1 = 4.00R$ and wire section 2 of diameter $D_2 = 2.00R$, connected by a tapered section. The wire is copper and carries a current. Assume that the current is uniformly distributed across any cross-sectional area through the wire's width. The electric potential change $V$ along the length $L = 2.00$ m shown in section 2 is 10.0 mV. The number of charge carriers per unit volume is $8.49 \times 10^{28}$ m$^-3$. What is the drift speed of the conduction electrons in section 1?

Answer:

Problem 35.

In Fig. 26-29, current is set up through a truncated right circular cone of resistivity 731 Ω·m, left radius $a = 2.00$ mm, right radius $b = 2.30$ mm, and length $L = 1.94$ cm. Assume that the current density is uniform across any cross section taken perpendicular to the length. What is the resistance of the cone?
Answer:

981 kΩ

Swimming during a storm. Figure 26-30 shows a swimmer at distance $D = 35.0$ m from a lightning strike to the water, with current $I = 78$ kA. The water has resistivity $30 \, \Omega \cdot \text{m}$, the width of the swimmer along a radial line from the strike is 0.70 m, and his resistance across that width is 4.00 kΩ. Assume that the current spreads through the water over a hemisphere centered on the strike point. What is the current through the swimmer?

Figure 26-30

sec. 26-6 A Microscopic View of Ohm’s Law

Show that, according to the free-electron model of electrical conduction in metals and classical physics, the resistivity of metals should be proportional to $\sqrt{T}$, where $T$ is the temperature in kelvins. (See Eq. 19-31.)

sec. 26-7 Power in Electric Circuits

In Fig. 26-31a, a 20 Ω resistor is connected to a battery. Figure 26-31b shows the increase of thermal energy $E_{\text{th}}$ in the resistor as a function of time $t$. The vertical scale is set by $E_{\text{th}, s} = 2.50$ mJ, and the horizontal scale is set by $t_s = 4.0$ s. What is the electric potential across the battery?

Figure 26-31
A certain brand of hot-dog cooker works by applying a potential difference of 120 V across opposite ends of a hot dog and allowing it to cook by means of the thermal energy produced. The current is 10.0 A, and the energy required to cook one hot dog is 60.0 kJ. If the rate at which energy is supplied is unchanged, how long will it take to cook three hot dogs simultaneously?

**Answer:**

150 s

Thermal energy is produced in a resistor at a rate of 100 W when the current is 3.00 A. What is the resistance?

---

A 120 V potential difference is applied to a space heater whose resistance is 14 Ω when hot. (a) At what rate is electrical energy transferred to thermal energy? (b) What is the cost for 5.0 h at US$0.05/kW \cdot h?

**Answer:**

(a) 1.0 kW; (b) US$0.25

In Fig. 26-32, a battery of potential difference \( V = 12 \text{ V} \) is connected to a resistive strip of resistance \( R = 6.0 \Omega \). When an electron moves through the strip from one end to the other, (a) in which direction in the figure does the electron move, (b) how much work is done on the electron by the electric field in the strip, and (c) how much energy is transferred to the thermal energy of the strip by the electron?

---

An unknown resistor is connected between the terminals of a 3.00 V battery. Energy is dissipated in the resistor at the rate of 0.540 W. The same resistor is then connected between the terminals of a 1.50 V battery. At what rate is energy now dissipated?

**Answer:**

0.135 W

A student kept his 9.0 V, 7.0 W radio turned on at full volume from 9:00 P.M. until 2:00 A.M. How much charge went through it?

---

A 1250 W radiant heater is constructed to operate at 115 V. (a) What is the current in the heater when the unit is operating? (b) What is the resistance of the heating coil? (c) How much thermal energy is produced in 1.0 h?

**Answer:**

(a) 10.9 A; (b) 10.6Ω; (c) 4.50 MJ

A copper wire of cross-sectional area \( 2.00 \times 10^{-6} \text{ m}^2 \) and length 4.00 m has a current of 2.00 A uniformly distributed across that area. (a) What is the magnitude of the electric field along the
wire? (b) How much electrical energy is transferred to thermal energy in 30 min?

**47** A heating element is made by maintaining a potential difference of 75.0 V across the length of a Nichrome wire that has a $2.60 \times 10^{-6}$ m$^2$ cross section. Nichrome has a resistivity of $5.00 \times 10^{-7}$ Ω · m. (a) If the element dissipates 5000 W, what is its length? (b) If 100 V is used to obtain the same dissipation rate, what should the length be?

**Answer:**

(a) 5.85 m; (b) 10.4 m

**48** *Explooding shoes*. The rain-soaked shoes of a person may explode if ground current from nearby lightning vaporizes the water. The sudden conversion of water to water vapor causes a dramatic expansion that can rip apart shoes. Water has density 1000 kg/m$^3$ and requires 2256 kJ/kg to be vaporized. If horizontal current lasts 2.00 ms and encounters water with resistivity 150 Ω m, length 12.0 cm, and vertical cross-sectional area $15 \times 10^{-5}$ m$^2$, what average current is required to vaporize the water?

**49** A 100 W lightbulb is plugged into a standard 120 V outlet. (a) How much does it cost per 31-day month to leave the light turned on continuously? Assume electrical energy costs US$0.06/k W · h. (b) What is the resistance of the bulb? (c) What is the current in the bulb?

**Answer:**

(a) US$4.46; (b) 144 Ω; (c) 0.833 A

**50** The current through the battery and resistors 1 and 2 in Fig. 26-33a is 2.00 A. Energy is transferred from the current to thermal energy $E_{th}$ in both resistors. Curves 1 and 2 in Fig. 26-33b give that thermal energy $E_{th}$ for resistors 1 and 2, respectively, as a function of time $t$. The vertical scale is set by $E_{th,s} = 40.0$ mJ, and the horizontal scale is set by $t_s = 5.00$ s. What is the power of the battery?

![Figure 26-33 Problem 50.](attachment:image)

**51** *SSM, WWW* Wire C and wire D are made from different materials and have length $L_C = L_D = 1.0$ m. The resistivity and diameter of wire C are $2.0 \times 10^{-6}$ Ω · m and 1.00 mm, and those of wire D are $1.0 \times 10^{-6}$ Ω · m and 0.50 mm. The wires are joined as shown in Fig. 26-34, and a current of 2.0 A is set up in them. What is the electric potential difference between (a) points 1 and 2 and (b) points 2 and 3? What is the rate at which energy is dissipated between (c) points 1 and 2 and (d) points 2 and 3?
Answer:

(a) 5.1 V; (b) 10 V; (c) 10 W; (d) 20 W

The current-density magnitude in a certain circular wire is $J = (2.75 \times 10^{10} \text{ A/m}^4)r^2$, where $r$ is the radial distance out to the wire's radius of 3.00 mm. The potential applied to the wire (end to end) is 60.0 V. How much energy is converted to thermal energy in 1.00 h?

A 120 V potential difference is applied to a space heater that dissipates 500 W during operation. (a) What is its resistance during operation? (b) At what rate do electrons flow through any cross section of the heater element?

Answer:

(a) 28.8 $\Omega$; (b) $2.60 \times 10^{19} \text{ s}^{-1}$

Figure 26-35a shows a rod of resistive material. The resistance per unit length of the rod increases in the positive direction of the $x$ axis. At any position $x$ along the rod, the resistance $dR$ of a narrow (differential) section of width $dx$ is given by $dR = 5.00x \, dx$, where $dR$ is in ohms and $x$ is in meters. Figure 26-35b shows such a narrow section. You are to slice off a length of the rod between $x = 0$ and some position $x = L$ and then connect that length to a battery with potential difference $V = 5.0$ V (Fig. 26-35c). You want the current in the length to transfer energy to thermal energy at the rate of 200 W. At what position $x = L$ should you cut the rod?

Additional Problems

55 SSM A Nichrome heater dissipates 500 W when the applied potential difference is 110 V and the wire temperature is 800°C. What would be the dissipation rate if the wire temperature were held at 200°C by immersing the wire in a bath of cooling oil? The applied potential difference remains the same, and $\alpha$ for Nichrome at 800°C is $4.0 \times 10^{-4} \text{ K}^{-1}$.

Answer:

660 W 57. 28.8 kC

A potential difference of 1.20 V will be applied to a 33.0 m length of 18-gauge copper wire
(diameter = 0.0400 in.). Calculate (a) the current, (b) the magnitude of the current density, (c) the magnitude of the electric field within the wire, and (d) the rate at which thermal energy will appear in the wire.

57 An 18.0 W device has 9.00 V across it. How much charge goes through the device in 4.00 h?

58 An aluminum rod with a square cross section is 1.3 m long and 5.2 mm on edge. (a) What is the resistance between its ends? (b) What must be the diameter of a cylindrical copper rod of length 1.3 m if its resistance is to be the same as that of the aluminum rod?

59 A cylindrical metal rod is 1.60 m long and 5.50 mm in diameter. The resistance between its two ends (at 20°C) is 1.09 × 10⁻³ Ω. (a) What is the material? (b) A round disk, 2.00 cm in diameter and 1.00 mm thick, is formed of the same material. What is the resistance between the round faces, assuming that each face is an equipotential surface?

Answer:

(a) silver; (b) 51.6 nΩ

60 The chocolate crumb mystery. This story begins with Problem 61 in Chapter 23 and continues through Chapters 24 and 25. The chocolate crumb powder moved to the silo through a pipe of radius $R$ with uniform speed $v$ and uniform charge density $\rho$. (a) Find an expression for the current $i$ (the rate at which charge on the powder moved) through a perpendicular cross section of the pipe. (b) Evaluate $i$ for the conditions at the factory: pipe radius $R = 5.0$ cm, speed $v = 2.0$ m/s, and charge density $\rho = 1.1 \times 10^{-3}$ C/m³.

If the powder were to flow through a change $V$ in electric potential, its energy could be transferred to a spark at the rate $P = iV$. (c) Could there be such a transfer within the pipe due to the radial potential difference discussed in Problem 70 of Chapter 24?

As the powder flowed from the pipe into the silo, the electric potential of the powder changed. The magnitude of that change was at least equal to the radial potential difference within the pipe (as evaluated in Problem 70 of Chapter 24). (d) Assuming that value for the potential difference and using the current found in (b) above, find the rate at which energy could have been transferred from the powder to a spark as the powder exited the pipe. (e) If a spark did occur at the exit and lasted for 0.20 σ (a reasonable expectation), how much energy would have been transferred to the spark?

Recall from Problem 60 in Chapter 23 that a minimum energy transfer of 150 mJ is needed to cause an explosion. (f) Where did the powder explosion most likely occur: in the powder cloud at the unloading bin (Problem 60 of Chapter 25), within the pipe, or at the exit of the pipe into the silo?

61 SSM A steady beam of alpha particles ($q = +2e$) traveling with constant kinetic energy 20 MeV carries a current of 0.25 μA. (a) If the beam is directed perpendicular to a flat surface, how many alpha particles strike the surface in 3.0 s? (b) At any instant, how many alpha particles are there in a given 20 cm length of the beam? (c) Through what potential difference is it necessary to accelerate each alpha particle from rest to bring it to an energy of 20 MeV?

Answer:

(a) $2.3 \times 10^{12}$; (b) $5.0 \times 10^{3}$; (c) 10 MV

62 A resistor with a potential difference of 200 V across it transfers electrical energy to thermal energy at the rate of 3000 W. What is the resistance of the resistor?
A 2.0 kW heater element from a dryer has a length of 80 cm. If a 10 cm section is removed, what power is used by the now shortened element at 120 V?

Answer:

2.4 kW

A cylindrical resistor of radius 5.0 mm and length 2.0 cm is made of material that has a resistivity of $3.5 \times 10^{-5} \Omega \cdot \text{m}$. What are (a) the magnitude of the current density and (b) the potential difference when the energy dissipation rate in the resistor is 1.0 W?

A potential difference $V$ is applied to a wire of cross-sectional area $A$, length $L$, and resistivity $\rho$. You want to change the applied potential difference and stretch the wire so that the energy dissipation rate is multiplied by 30.0 and the current is multiplied by 4.00. Assuming the wire's density does not change, what are (a) the ratio of the new length to $L$ and (b) the ratio of the new cross-sectional area to $A$?

Answer:

(a) 1.37; (b) 0.730

The headlights of a moving car require about 10 A from the 12 V alternator, which is driven by the engine. Assume the alternator is 80% efficient (its output electrical power is 80% of its input mechanical power), and calculate the horsepower the engine must supply to run the lights.

A 500 W heating unit is designed to operate with an applied potential difference of 115 V. (a) By what percentage will its heat output drop if the applied potential difference drops to 110 V? Assume no change in resistance. (b) If you took the variation of resistance with temperature into account, would the actual drop in heat output be larger or smaller than that calculated in (a)?

Answer:

(a) -8.6%; (b) smaller

The copper windings of a motor have a resistance of 50 $\Omega$ at 20°C when the motor is idle. After the motor has run for several hours, the resistance rises to 58 $\Omega$. What is the temperature of the windings now? Ignore changes in the dimensions of the windings. (Use Table 26-1.)

How much electrical energy is transferred to thermal energy in 2.00 h by an electrical resistance of 400 $\Omega$ when the potential applied across it is 90.0 V?

Answer:

146 kJ

A caterpillar of length 4.0 cm crawls in the direction of electron drift along a 5.2-mm-diameter bare copper wire that carries a uniform current of 12 A. (a) What is the potential difference between the two ends of the caterpillar? (b) Is its tail positive or negative relative to its head? (c) How much time does the caterpillar take to crawl 1.0 cm if it crawls at the drift speed of the electrons in the wire? (The number of charge carriers per unit volume is $8.49 \times 10^{28} \text{m}^{-3}$.)

SSM (a) At what temperature would the resistance of a copper conductor be double its resistance at 20.0°C? (Use 20.0°C as the reference point in Eq. 26-17; compare your answer with Fig. 26-10.) (b) Does this same “doubling temperature” hold for all copper conductors, regardless of shape or size?
(a) 250°C; (b) yes

72 A steel trolley-car rail has a cross-sectional area of 56.0 cm². What is the resistance of 10.0 km of rail? The resistivity of the steel is 3.00 × 10⁻⁷ Ω · m.

73 A coil of current-carrying Nichrome wire is immersed in a liquid. (Nichrome is a nickel–chromium–iron alloy commonly used in heating elements.) When the potential difference across the coil is 12 V and the current through the coil is 5.2 A, the liquid evaporates at the steady rate of 21 mg/s. Calculate the heat of vaporization of the liquid (see Section 18-4).

Answer:

3.0 × 10⁶ J/kg

74 The current density in a wire is uniform and has magnitude 2.0 × 10⁶ A/m², the wire’s length is 5.0 m, and the density of conduction electrons is 8.49 × 10²⁸ m⁻³. How long does an electron take (on the average) to travel the length of the wire?

75 A certain x-ray tube operates at a current of 7.00 mA and a potential difference of 80.0 kV. What is its power in watts?

Answer:

560 W

76 A current is established in a gas discharge tube when a sufficiently high potential difference is applied across the two electrodes in the tube. The gas ionizes; electrons move toward the positive terminal and singly charged positive ions toward the negative terminal. (a) What is the current in a hydrogen discharge tube in which 3.1 × 10¹⁸ electrons and 1.1 × 10¹⁸ protons move past a cross-sectional area of the tube each second? (b) Is the direction of the current density \( \mathbf{J} \) toward or away from the negative terminal?

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sec. 27-6 Potential Difference Between Two Points

*1 SSM WWW In Fig. 27-25, the ideal batteries have emfs \( \mathcal{E}_1 = 12 \) V and \( \mathcal{E}_2 = 6.0 \) V. What are (a) the current, the dissipation rate in (b) resistor 1 (4.0 Ω) and (c) resistor 2 (8.0 Ω), and the energy transfer rate in (d) battery 1 and (e) battery 2? Is energy being supplied or absorbed by (f) battery 1 and (g) battery 2?
Problem 1.

Answer:

(a) 0.50 A; (b) 1.0 W; (c) 2.0 W; (d) 6.0 W; (e) 3.0 W; (f) supplied; (g) absorbed

In Fig. 27-26, the ideal batteries have emfs $E_1 = 150$ V and $E_2 = 50$ V and the resistances are $R_1 = 3.0$ $\Omega$ and $R_2 = 2.0$ $\Omega$. If the potential at $P$ is 100 V, what is it at $Q$?

Problem 2.

A car battery with a 12 V emf and an internal resistance of 0.040 $\Omega$ is being charged with a current of 50 A. What are (a) the potential difference $V$ across the terminals, (b) the rate $P_r$ of energy dissipation inside the battery, and (c) the rate $P_{emf}$ of energy conversion to chemical form? When the battery is used to supply 50 A to the starter motor, what are (d) $V$ and (e) $P_r$?

Answer:

(a) 14 V; (b) $1.0 \times 10^2$ W; (c) $6.0 \times 10^2$ W; (d) 10 V; (e) $1.0 \times 10^3$ W

Problem 3.

Figure 27-27 shows a circuit of four resistors that are connected to a larger circuit. The graph below the circuit shows the electric potential $V(x)$ as a function of position $x$ along the lower branch of the circuit, through resistor 4; the potential $V_A$ is 12.0 V. The graph above the circuit shows the electric potential $V(x)$ versus position $x$ along the upper branch of the circuit, through resistors 1, 2, and 3; the potential differences are $\Delta V_B = 2.00$ V and $\Delta V_C = 5.00$ V. Resistor 3 has a resistance of 200 $\Omega$. What is the resistance of (a) resistor 1 and (b) resistor 2?
5. A 5.0 A current is set up in a circuit for 6.0 min by a rechargeable battery with a 6.0 V emf. By how much is the chemical energy of the battery reduced?

Answer:
11 kJ

6. A standard flashlight battery can deliver about 2.0 W · h of energy before it runs down. (a) If a battery costs US$0.80, what is the cost of operating a 100 W lamp for 8.0 h using batteries? (b) What is the cost if energy is provided at the rate of US$0.06 per kilowatt-hour?

Answer:
(a) 80 J; (b) 67 J; (c) 13 J

7. A wire of resistance 5.0 Ω is connected to a battery whose emf $\mathcal{E}$ is 2.0 V and whose internal resistance is 1.0 Ω. In 2.0 min, how much energy is (a) transferred from chemical form in the battery, (b) dissipated as thermal energy in the wire, and (c) dissipated as thermal energy in the battery?

Answer:
(a) 80 J; (b) 67 J; (c) 13 J

8. A certain car battery with a 12.0 V emf has an initial charge of 120 A · h. Assuming that the potential across the terminals stays constant until the battery is completely discharged, for how many hours can it deliver energy at the rate of 100 W?

9. (a) In electron-volts, how much work does an ideal battery with a 12.0 V emf do on an electron that passes through the battery from the positive to the negative terminal? (b) If $3.40 \times 10^{18}$ electrons pass through each second, what is the power of the battery in watts?

Answer:
(a) 12.0 eV; (b) 6.53 W

10. (a) In Fig. 27-28, what value must $R$ have if the current in the circuit is to be 1.0 mA? Take $\mathcal{E}_1 =$
2.0 V, \( \mathcal{E}_2 = 3.0 \) V, and \( r_1 = r_2 = 3.0 \) \( \Omega \). (b) What is the rate at which thermal energy appears in \( R \)?

\[ \text{Figure 27-28} \] Problem 10.

**11 SSM** In Fig. 27-29, circuit section \( AB \) absorbs energy at a rate of 50 W when current \( i = 1.0 \) A through it is in the indicated direction. Resistance \( R = 2.0 \) \( \Omega \). (a) What is the potential difference between \( A \) and \( B \)? Emf device \( X \) lacks internal resistance. (b) What is its emf? (c) Is point \( B \) connected to the positive terminal of \( X \) or to the negative terminal?

\[ \text{Figure 27-29} \] Problem 11.

**Answer:**

(a) 50 V; (b) 48 V; (c) negative

**12** Figure 27-30 shows a resistor of resistance \( R = 6.00 \) \( \Omega \) connected to an ideal battery of emf \( \mathcal{E} = 12.0 \) V by means of two copper wires. Each wire has length 20.0 cm and radius 1.00 mm. In dealing with such circuits in this chapter, we generally neglect the potential differences along the wires and the transfer of energy to thermal energy in them. Check the validity of this neglect for the circuit of Fig. 27-30: What is the potential difference across (a) the resistor and (b) each of the two sections of wire? At what rate is energy lost to thermal energy in (c) the resistor and (d) each section of wire?

\[ \text{Figure 27-30} \] Problem 12.

**13** A 10-km-long underground cable extends east to west and consists of two parallel wires, each of which has resistance 13 \( \Omega \)/km. An electrical short develops at distance \( x \) from the west end when a conducting path of resistance \( R \) connects the wires (Fig. 27-31). The resistance of the wires and the short is then 100 \( \Omega \) when measured from the east end and 200 \( \Omega \) when measured from the west end. What are (a) \( x \) and (b) \( R \)?
Problem 13.

Answer:

(a) 6.9 km; (b) 20 \( \Omega \)

In Fig. 27-32, both batteries have emf \( \mathcal{E} = 1.20 \) V and the external resistance \( R \) is a variable resistor. Figure 27-32b gives the electric potentials \( V \) between the terminals of each battery as functions of \( R \): Curve 1 corresponds to battery 1, and curve 2 corresponds to battery 2. The horizontal scale is set by \( R_s = 0.20 \Omega \). What is the internal resistance of (a) battery 1 and (b) battery 2?

Figure 27-32

Problem 14.

The current in a single-loop circuit with one resistance \( R \) is 5.0 A. When an additional resistance of 2.0 \( \Omega \) is inserted in series with \( R \), the current drops to 4.0 A. What is \( R \)?

Answer:

8.0 \( \Omega \)

A solar cell generates a potential difference of 0.10 V when a 500 \( \Omega \) resistor is connected across it, and a potential difference of 0.15 V when a 1000 \( \Omega \) resistor is substituted. What are the (a) internal resistance and (b) emf of the solar cell? (c) The area of the cell is 5.0 cm\(^2\), and the rate per unit area at which it receives energy from light is 2.0 mW/cm\(^2\). What is the efficiency of the cell for converting light energy to thermal energy in the 1000 \( \Omega \) external resistor?

In Fig. 27-33, battery 1 has emf \( \mathcal{E}_1 = 12.0 \) V and internal resistance \( r_1 = 0.016 \) and battery 2 has emf \( \mathcal{E}_2 = 12.0 \) V and internal resistance \( r_2 = 0.012 \Omega \). The batteries are connected in series with an external resistance \( R \). (a) What \( R \) value makes the terminal-to-terminal potential difference of one of the batteries zero? (b) Which battery is that?
Answer:

(a) 0.004 $\Omega$; (b) 1

**sec. 27-7 Multiloop Circuits**

•18 In Fig. 27-9, what is the potential difference $V_d - V_c$ between points $d$ and $c$ if $\mathcal{E}_1 = 4.0$ V, $\mathcal{E}_2 = 1.0$ V, $R_1 = R_2 = 10 \Omega$, and $R_3 = 5.0 \Omega$, and the battery is ideal?

•19 A total resistance of 3.00 $\Omega$ is to be produced by connecting an unknown resistance to a 12.0 $\Omega$ resistance. (a) What must be the value of the unknown resistance, and (b) should it be connected in series or in parallel?

Answer:

(a) 4.00 $\Omega$; (b) parallel

•20 When resistors 1 and 2 are connected in series, the equivalent resistance is 16.0 $\Omega$. When they are connected in parallel, the equivalent resistance is 3.0 $\Omega$. What are (a) the smaller resistance and (b) the larger resistance of these two resistors?

•21 Four 18.0 $\Omega$ resistors are connected in parallel across a 25.0 V ideal battery. What is the current through the battery?

Answer:

5.56 A

•22 Figure 27-34 shows five 5.00 resistors. Find the equivalent resistance between points (a) $F$ and $H$ and (b) $F$ and $G$. (Hint: For each pair of points, imagine that a battery is connected across the pair.)

•23 In Fig. 27-35, $R_1 = 100 \Omega$, $R_2 = 50 \Omega$, and the ideal batteries have emfs $\mathcal{E}_1 = 6.0$ V, $\mathcal{E}_2 = 5.0$ V, and $\mathcal{E}_3 = 4.0$ V. Find (a) the current in resistor 1, (b) the current in resistor 2, and (c) the potential difference between points $a$ and $b$. 

---

**Figure 27-33** Problem 17.

**Figure 27-34** Problem 22.
Problem 23.

Answer:

(a) 50 mA; (b) 60 mA; (c) 9.0 V

Problem 24.

In Fig. 27-36, \( R_1 = R_2 = 4.00 \, \Omega \) and \( R_3 = 2.50 \, \Omega \). Find the equivalent resistance between points \( D \) and \( E \). (Hint: Imagine that a battery is connected across those points.)

Problem 25. Nine copper wires of length \( l \) and diameter \( d \) are connected in parallel to form a single composite conductor of resistance \( R \). What must be the diameter \( D \) of a single copper wire of length \( l \) if it is to have the same resistance?

Answer:

\( 3d \)

Problem 26. Figure 27-37 shows a battery connected across a uniform resistor \( R_0 \). A sliding contact can move across the resistor from \( x = 0 \) at the left to \( x = 10 \, \text{cm} \) at the right. Moving the contact changes how much resistance is to the left of the contact and how much is to the right. Find the rate at which energy is dissipated in resistor \( R \) as a function of \( x \). Plot the function for \( \mathcal{E} = 50 \, \text{V} \), \( R = 2000 \, \Omega \), and \( R_0 = 100 \, \Omega \).
Side flash. Figure 27-38 indicates one reason no one should stand under a tree during a lightning storm. If lightning comes down the side of the tree, a portion can jump over to the person, especially if the current on the tree reaches a dry region on the bark and thereafter must travel through air to reach the ground. In the figure, part of the lightning jumps through distance $d$ in air and then travels through the person (who has negligible resistance relative to that of air). The rest of the current travels through air alongside the tree, for a distance $h$. If $d/h = 0.400$ and the total current is $I = 5000 \text{ A}$, what is the current through the person?

![Lightning current diagram](image)

Figure 27-38

Problem 27.

Answer:

$3.6 \times 10^3 \text{ A}$

The ideal battery in Fig. 27-39a has emf $\mathcal{E} = 6.0 \text{ V}$. Plot 1 in Fig. 27-39b gives the electric potential difference $V$ that can appear across resistor 1 of the circuit versus the current $i$ in that resistor. The scale of the $V$ axis is set by $V_s = 18.0 \text{ V}$, and the scale of the $i$ axis is set by $i_s = 3.00 \text{ mA}$. Plots 2 and 3 are similar plots for resistors 2 and 3, respectively. What is the current in resistor 2?

![Circuit diagram](image)

Figure 27-39

Problem 28.

In Fig. 27-40, $R_1 = 6.00 \Omega$, $R_2 = 18.0 \Omega$, and the ideal battery has emf $\mathcal{E} = 12.0 \text{ V}$. What are the (a) size and (b) direction (left or right) of current $i_1$? (c) How much energy is dissipated by all four resistors in 1.00 min?
Figure 27-40 Problem 29.

Answer:

(a) 0.333 A; (b) right; (c) 720 J

**30** In Fig. 27-41, the ideal batteries have emfs $\mathcal{E}_1 = 10.0 \text{ V}$ and $\mathcal{E}_2 = 0.500 \mathcal{E}_1$, and the resistances are each $4.00 \Omega$. What is the current in (a) resistance 2 and (b) resistance 3?

Figure 27-41 Problems 30, 41, and 88.

**31** In Fig. 27-42, the ideal batteries have emfs $\mathcal{E}_1 = 5.0 \text{ V}$ and $\mathcal{E}_2 = 12 \text{ V}$, the resistances are each $2.0 \Omega$, and the potential is defined to be zero at the grounded point of the circuit. What are potentials (a) $V_1$ and (b) $V_2$ at the indicated points?

Figure 27-42 Problem 31.

Answer:

(a) -11 V; (b) -9.0 V

**32** Both batteries in Fig. 27-43a are ideal. Emf $\mathcal{E}_1$ of battery 1 has a fixed value, but emf $\mathcal{E}_2$ of battery 2 can be varied between 1.0 V and 10 V. The plots in Fig. 27-43b give the currents through the two batteries as a function of $\mathcal{E}_2$. The vertical scale is set by $i_s = 0.20 \text{ A}$. You must decide which plot corresponds to which battery, but for both plots, a negative current occurs when
the direction of the current through the battery is opposite the direction of that battery’s emf. What are (a) emf \( \mathcal{E}_1 \), (b) resistance \( R_1 \), and (c) resistance \( R_2 \)?

![Diagram](image)

**Figure 27-43** Problem 32.

In Fig. 27-44, the current in resistance 6 is \( i_6 = 1.40 \) A and the resistances are \( R_1 = R_2 = R_3 = 2.00 \) \( \Omega \), \( R_4 = 16.0 \) \( \Omega \), \( R_5 = 8.00 \) \( \Omega \), and \( R_6 = 4.00 \) \( \Omega \). What is the emf of the ideal battery?

![Diagram](image)

**Figure 27-44** Problem 33.

**Answer:**

48.3 V

The resistances in Figs. 27-45a and 27-45b are all 6.0 \( \Omega \), and the batteries are ideal 12 V batteries. (a) When switch S in Fig. 27-45a is closed, what is the change in the electric potential \( V_1 \) across resistor 1, or does \( V_1 \) remain the same? (b) When switch S in Fig. 27-45b is closed, what is the change in \( V_1 \) across resistor 1, or does \( V_1 \) remain the same?

![Diagram](image)

**Figure 27-45** Problem 34.

In Fig. 27-46, \( \mathcal{E} = 12.0 \) V, \( R_1 = 2000 \) \( \Omega \), \( R_2 = 3000 \) \( \Omega \), and \( R_3 = 4000 \) \( \Omega \). What are the potential differences (a) \( V_A - V_B \), (b) \( V_B - V_C \), (c) \( V_C - V_D \), and (d) \( V_A - V_C \)?

![Diagram](image)
Answer:

(a) 5.25 V; (b) 1.50 V; (c) 5.25 V; (d) 6.75 V

In Fig. 27-47, $E_1 = 6.00 \, \text{V}$, $E_2 = 12.0 \, \text{V}$, $R_1 = 100 \, \Omega$, $R_2 = 200 \, \Omega$, and $R_3 = 300 \, \Omega$. One point of the circuit is grounded ($V = 0$). What are the (a) size and (b) direction (up or down) of the current through resistance 1, the (c) size and (d) direction (left or right) of the current through resistance 2, and the (e) size and (f) direction of the current through resistance 3? (g) What is the electric potential at point $A$?

Answer:

(a) 1.43 $\Omega$

In Fig. 27-49 shows a section of a circuit. The resistances are $R_1 = 2.0 \, \Omega$, $R_2 = 4.0 \, \Omega$, and $R_3 = 6.0 \, \Omega$, and the indicated current is $i = 6.0 \, \text{A}$. The electric potential difference between points $A$ and $B$ that connect the section to the rest of the circuit is $V_A - V_B = 78 \, \text{V}$. (a) Is the device represented by “Box” absorbing or providing energy to the circuit, and (b) at what rate?
**Problem 38.**

In Fig. 27-50, two batteries of emf $\mathcal{E} = 12.0 \text{ V}$ and internal resistance $r = 0.300 \text{ $\Omega$}$ are connected in parallel across a resistance $R$. (a) For what value of $R$ is the dissipation rate in the resistor a maximum? (b) What is that maximum?

**Answer:**

(a) $0.150 \text{ $\Omega$}$; (b) $240 \text{ W}$

---

**Problem 40.**

Two identical batteries of emf $\mathcal{E} = 12.0 \text{ V}$ and internal resistance $r = 0.200 \text{ $\Omega$}$ are to be connected to an external resistance $R$, either in parallel (Fig. 27-50) or in series (Fig. 27-51). If $R = 2.00r$, what is the current $i$ in the external resistance in the (a) parallel and (b) series arrangements? (c) For which arrangement is $i$ greater? If $R = r/2.00$, what is $i$ in the external resistance in the (d) parallel and (e) series arrangements? (f) For which arrangement is $i$ greater now?

---

**Problem 41.**

In Fig. 27-41, $\mathcal{E}_1 = 3.00 \text{ V}$, $\mathcal{E}_2 = 1.00 \text{ V}$, $R_1 = 4.00 \text{ $\Omega$}$, $R_2 = 2.00 \text{ $\Omega$}$, $R_3 = 5.00 \text{ $\Omega$}$, and both batteries are ideal. What is the rate at which energy is dissipated in (a) $R_1$, (b) $R_2$, and (c) $R_3$? What is the power of (d) battery 1 and (e) battery 2?
**Answer:**

(a) 0.709 W; (b) 0.050 W; (c) 0.346 W; (d) 1.26 W; (e) -0.158 W

**42** In Fig. 27-52, an array of $n$ parallel resistors is connected in series to a resistor and an ideal battery. All the resistors have the same resistance. If an identical resistor were added in parallel to the parallel array, the current through the battery would change by 1.25%. What is the value of $n$?

![Figure 27-52 Problem 42.](image)

**43** You are given a number of 10 Ω resistors, each capable of dissipating only 1.0 W without being destroyed. What is the minimum number of such resistors that you need to combine in series or in parallel to make a 10 Ω resistance that is capable of dissipating at least 5.0 W?

**Answer:**

9

**44** In Fig. 27-53, $R_1 = 100$ Ω, $R_2 = R_3 = 50.0$ Ω, $R_4 = 75.0$ Ω, and the ideal battery has emf $\mathcal{E} = 6.00$ V. (a) What is the equivalent resistance? What is $i$ in (b) resistance 1, (c) resistance 2, (d) resistance 3, and (e) resistance 4?

![Figure 27-53 Problems 44 and 48.](image)

**45** In Fig. 27-54, the resistances are $R_1 = 1.0$ Ω and $R_2 = 2.0$ Ω, and the ideal batteries have emfs $\mathcal{E}_1 = 2.0$ V and $\mathcal{E}_2 = \mathcal{E}_3 = 4.0$ V. What are the (a) size and (b) direction (up or down) of the current in battery 1, the (c) size and (d) direction of the current in battery 2, and the (e) size and (f) direction of the current in battery 3? (g) What is the potential difference $V_a - V_b$?

![Figure 27-54](image)
Problem 45.

Answer:

(a) 0.67 A; (b) down; (c) 0.33 A; (d) up; (e) 0.33 A; (f) up; (g) 3.3 V

**46** In Fig. 27-55a, resistor 3 is a variable resistor and the ideal battery has emf \( \varepsilon = 12 \) V. Figure 27-55b gives the current \( i \) through the battery as a function of \( R_3 \). The horizontal scale is set by \( R_{3r} = 20 \, \Omega \). The curve has an asymptote of 2.0 mA as \( R_3 \to \infty \). What are (a) resistance \( R_1 \) and (b) resistance \( R_2 \)?

![Figure 27-55](image)

Problem 46.

**47** SSM A copper wire of radius \( a = 0.250 \) mm has an aluminum jacket of outer radius \( b = 0.380 \) mm. There is a current \( i = 2.00 \) A in the composite wire. Using Table 26-1, calculate the current in (a) the copper and (b) the aluminum. (c) If a potential difference \( V = 12.0 \) V between the ends maintains the current, what is the length of the composite wire?

Answer:

(a) 1.11 A; (b) 0.893 A; (c) 126 m

**48** In Fig. 27-53, the resistors have the values \( R_1 = 7.00 \) \( \Omega \), \( R_2 = 12.0 \) \( \Omega \), and \( R_3 = 4.00 \) \( \Omega \), and the ideal battery’s emf is \( \varepsilon = 24.0 \) V. For what value of \( R_4 \) will the rate at which the battery transfers energy to the resistors equal (a) 60.0 W, (b) the maximum possible rate \( P_{\text{max}} \), and (c) the minimum possible rate \( P_{\text{min}} \)? What are (d) \( P_{\text{max}} \) and (e) \( P_{\text{min}} \)?

sec. 27-8 The Ammeter and the Voltmeter

**49** ILW (a) In Fig. 27-56, what does the ammeter read if \( \varepsilon = 5.0 \) V (ideal battery), \( R_1 = 2.0 \, \Omega \), \( R_2 = 4.0 \, \Omega \), and \( R_3 = 6.0 \, \Omega \)? (b) The ammeter and battery are now interchanged. Show that the ammeter reading is unchanged.

![Figure 27-56](image)
Answer:

(a) 0.45 A

50 In Fig. 27-57, $R_1 = 2.00R$, the ammeter resistance is zero, and the battery is ideal. What multiple of $\mathcal{E}/R$ gives the current in the ammeter?

![Figure 27-57 Problem 50.](image)

51 In Fig. 27-58, a voltmeter of resistance $R_V = 300 \, \Omega$ and an ammeter of resistance $R_A = 3.00 \, \Omega$ are being used to measure a resistance $R$ in a circuit that also contains a resistance $R_0 = 100 \, \Omega$ and an ideal battery of emf $\mathcal{E} = 12.0 \, \text{V}$. Resistance $R$ is given by $R = V/i$, where $V$ is the potential across $R$ and $i$ is the ammeter reading. The voltmeter reading is $V$, which is $V$ plus the potential difference across the ammeter. Thus, the ratio of the two meter readings is not $R$ but only an apparent resistance $R' = V/i$. If $R = 85.0 \, \Omega$, what are (a) the ammeter reading, (b) the voltmeter reading, and (c) $R'$? (d) If $R_A$ is decreased, does the difference between $R'$ and $R$ increase, decrease, or remain the same?

![Figure 27-58 Problem 51.](image)

Answer:

(a) 55.2 mA; (b) 4.86 V; (c) 88.0 $\Omega$; (d) decrease

52 A simple ohmmeter is made by connecting a 1.50 V flashlight battery in series with a resistance $R$ and an ammeter that reads from 0 to 1.00 mA, as shown in Fig. 27-59. Resistance $R$ is adjusted so that when the clip leads are shorted together, the meter deflects to its full-scale value of 1.00 mA. What external resistance across the leads results in a deflection of (a) 10.0%, (b) 50.0%, and (c) 90.0% of full scale? (d) If the ammeter has a resistance of 20.0 $\Omega$ and the internal resistance of the battery is negligible, what is the value of $R$?

![Figure 27-59 Problem 52.](image)
**Problem 52.**

In Fig. 27-14, assume that $\mathcal{E} = 3.0 \text{ V}$, $r = 100 \ \Omega$, $R_1 = 250 \ \Omega$, and $R_2 = 300 \ \Omega$. If the voltmeter resistance $R_V$ is $5.0 \text{ k}\Omega$, what percent error does it introduce into the measurement of the potential difference across $R_1$? Ignore the presence of the ammeter.

**Answer:**

-3.0%

**Problem 54.**

When the lights of a car are switched on, an ammeter in series with them reads 10.0 A and a voltmeter connected across them reads 12.0 V (Fig. 27-60). When the electric starting motor is turned on, the ammeter reading drops to 8.00 A and the lights dim somewhat. If the internal resistance of the battery is 0.0500 $\Omega$ and that of the ammeter is negligible, what are (a) the emf of the battery and (b) the current through the starting motor when the lights are on?

**Problem 55.**

In Fig. 27-61, $R_s$ is to be adjusted in value by moving the sliding contact across it until points $a$ and $b$ are brought to the same potential. (One tests for this condition by momentarily connecting a sensitive ammeter between $a$ and $b$; if these points are at the same potential, the ammeter will not deflect.) Show that when this adjustment is made, the following relation holds: $R_x = R_s R_2 / R_1$. An unknown resistance ($R_x$) can be measured in terms of a standard ($R_s$) using this device, which is called a Wheatstone bridge.
Problem 55.

In Fig. 27-62, a voltmeter of resistance \( R_V = 300 \, \Omega \) and an ammeter of resistance \( R_A = 3.00 \, \Omega \) are being used to measure a resistance \( R \) in a circuit that also contains a resistance \( R_0 = 100 \, \Omega \) and an ideal battery of emf \( \mathcal{E} = 12.0 \, V \). Resistance \( R \) is given by \( R = V/i \), where \( V \) is the voltmeter reading and \( i \) is the current in resistance \( R \). However, the ammeter reading is not \( i \) but rather \( i' \), which is \( i \) plus the current through the voltmeter. Thus, the ratio of the two meter readings is not \( R \) but only an apparent resistance \( R' = V/i' \). If \( R = 85.0 \, \Omega \), what are (a) the ammeter reading, (b) the voltmeter reading, and (c) \( R' \)? (d) If \( R_V \) is increased, does the difference between \( R' \) and \( R \) increase, decrease, or remain the same?

Problem 56.

sec. 27-9 RC Circuits

Switch S in Fig. 27-63 is closed at time \( t = 0 \), to begin charging an initially uncharged capacitor of capacitance \( C = 15.0 \, \mu F \) through a resistor of resistance \( R = 20.0 \, \Omega \). At what time is the potential across the capacitor equal to that across the resistor?

Answer:
0.208 ms

*58. In an RC series circuit, emf $\mathcal{E} = 12.0$ V, resistance $R = 1.40$ MΩ, and capacitance $C = 1.80 \ \mu$F. (a) Calculate the time constant. (b) Find the maximum charge that will appear on the capacitor during charging. (c) How long does it take for the charge to build up to $16.0 \ \mu$C?

*59 SSM What multiple of the time constant $\tau$ gives the time taken by an initially uncharged capacitor in an RC series circuit to be charged to 99.0% of its final charge?

Answer:

4.61

*60 A capacitor with initial charge $q_0$ is discharged through a resistor. What multiple of the time constant $\tau$ gives the time the capacitor takes to lose (a) the first one-third of its charge and (b) two-thirds of its charge?

*61 ILW A 15.0 kΩ resistor and a capacitor are connected in series, and then a 12.0 V potential difference is suddenly applied across them. The potential difference across the capacitor rises to 5.00 V in 1.30 $\mu$s. (a) Calculate the time constant of the circuit. (b) Find the capacitance of the capacitor.

Answer:

(a) 2.41 $\mu$s; (b) 161 pF

*62 Figure 27-64 shows the circuit of a flashing lamp, like those attached to barrels at highway construction sites. The fluorescent lamp L (of negligible capacitance) is connected in parallel across the capacitor C of an RC circuit. There is a current through the lamp only when the potential difference across it reaches the breakdown voltage $V_L$; then the capacitor discharges completely through the lamp and the lamp flashes briefly. For a lamp with breakdown voltage $V_L = 72.0$ V, wired to a 95.0 V ideal battery and a 0.150 $\mu$F capacitor, what resistance $R$ is needed for two flashes per second?

![Figure 27-64](image)

*63 SSM WWW In the circuit of Fig. 27-65, $\mathcal{E} = 1.2$ kV, $C = 6.5$ $\mu$F, $R_1 = R_2 = R_3 = 0.73$ MΩ. With $C$ completely uncharged, switch S is suddenly closed (at $t = 0$). At $t = 0$, what are (a) current $i_1$ in resistor 1, (b) current $i_2$ in resistor 2, and (c) current $i_3$ in resistor 3? At $t = \infty$ (that is, after many time constants), what are (d) $i_1$, (e) $i_2$, and (f) $i_3$? What is the potential difference $V_2$ across resistor 2 at (g) $t = 0$ and (h) $t = \infty$? (i) Sketch $V_2$ versus $t$ between these two extreme times.
Problem 63.

Answer:

(a) 1.1 mA; (b) 0.55 mA; (c) 0.55 mA; (d) 0.82 mA; (e) 0.82 mA; (f) 0; (g) $4.0 \times 10^2$ V; (h) $6.0 \times 10^2$ V

A capacitor with an initial potential difference of 100 V is discharged through a resistor when a switch between them is closed at $t = 0$. At $t = 10.0$ s, the potential difference across the capacitor is 1.00 V. (a) What is the time constant of the circuit? (b) What is the potential difference across the capacitor at $t = 17.0$ s?

In Fig. 27-66, $R_1 = 10.0 \text{k}\Omega$, $R_2 = 15.0 \text{k}\Omega$, $C = 0.400 \mu\text{F}$, and the ideal battery has emf $\mathcal{E} = 20.0$ V. First, the switch is closed a long time so that the steady state is reached. Then the switch is opened at time $t = 0$. What is the current in resistor 2 at $t = 4.00$ ms?

Answer:

411 $\mu$A

Figure 27-67 displays two circuits with a charged capacitor that is to be discharged through a resistor when a switch is closed. In Fig. 27-67a, $R_1 = 20.0 \Omega$ and $C_1 = 5.00 \mu\text{F}$. In Fig. 27-67b, $R_2 = 10.0 \Omega$ and $C_2 = 8.00 \mu\text{F}$. The ratio of the initial charges on the two capacitors is $q_{02}/q_{01} = 1.50$. At time $t = 0$, both switches are closed. At what time $t$ do the two capacitors have the same charge?

The potential difference between the plates of a leaky (meaning that charge leaks from one plate to the other) $2.0 \mu\text{F}$ capacitor drops to one-fourth its initial value in 2.0 s. What is the equivalent resistance between the capacitor plates?
Answer:

0.72 MΩ

**68** A 1.0 μF capacitor with an initial stored energy of 0.50 J is discharged through a 1.0 MΩ resistor. (a) What is the initial charge on the capacitor? (b) What is the current through the resistor when the discharge starts? Find an expression that gives, as a function of time \( t \), (c) the potential difference \( V_C \) across the capacitor, (d) the potential difference \( V_R \) across the resistor, and (e) the rate at which thermal energy is produced in the resistor.

***69*** A 3.00 MΩ resistor and a 1.00 μF capacitor are connected in series with an ideal battery of emf \( \mathcal{E} = 4.00 \) V. At 1.00 s after the connection is made, what is the rate at which (a) the charge of the capacitor is increasing, (b) energy is being stored in the capacitor, (c) thermal energy is appearing in the resistor, and (d) energy is being delivered by the battery?

Answer:

(a) 0.955 μC/s; (b) 1.08 μW; (c) 2.74 μW; (d) 3.82 μW

Additional Problems

70 Each of the six real batteries in Fig. 27-68 has an emf of 20 V and a resistance of 4.0 Ω. (a) What is the current through the (external) resistance \( R = 4.0 \) Ω? (b) What is the potential difference across each battery? (c) What is the power of each battery? (d) At what rate does each battery transfer energy to internal thermal energy?

![Figure 27-68](Image)

**Figure 27-68** Problem 70.

71 In Fig. 27-69, \( R_1 = 20.0 \) Ω, \( R_2 = 10.0 \) Ω, and the ideal battery has emf \( \mathcal{E} = 120 \) V. What is the current at point \( a \) if we close (a) only switch \( S_1 \), (b) only switches \( S_1 \) and \( S_2 \), and (c) all three switches?

![Figure 27-69](Image)

**Figure 27-69** Problem 71.
Answer:

(a) 3.00 A; (b) 3.75 A; (c) 3.94 A

In Fig. 27-70, the ideal battery has emf $\mathcal{E} = 30.0$ V, and the resistances are $R_1 = R_2 = 14$ $\Omega$, $R_3 = R_4 = R_5 = 6.0$ $\Omega$, $R_6 = 2.0$ $\Omega$, and $R_7 = 1.5$ $\Omega$. What are currents (a) $i_2$, (b) $i_3$, (c) $i_1$, (d) $i_3$, and (e) $i_5$?

Figure 27-70 Problem 72.

Wires $A$ and $B$, having equal lengths of 40.0 m and equal diameters of 2.60 mm, are connected in series. A potential difference of 60.0 V is applied between the ends of the composite wire. The resistances are $R_A = 0.127$ $\Omega$ and $R_B = 0.729$ $\Omega$. For wire $A$, what are (a) magnitude $J$ of the current density and (b) potential difference $V$? (c) Of what type material is wire $A$ made (see Table 26-1)? For wire $B$, what are (d) $J$ and (e) $V$? (f) Of what type material is $B$ made?

Answer:

(a) $1.32 \times 10^7$ A/m$^2$; (b) 8.90 V; (c) copper; (d) $1.32 \times 10^7$ A/m$^2$; (e) 51.1 V; (f) iron

What are the (a) size and (b) direction (up or down) of current $i$ in Fig. 27-71, where all resistances are 4.0 $\Omega$ and all batteries are ideal and have an emf of 10 V? (Hint: This can be answered using only mental calculation.)
Suppose that, while you are sitting in a chair, charge separation between your clothing and the chair puts you at a potential of 200 V, with the capacitance between you and the chair at 150 pF. When you stand up, the increased separation between your body and the chair decreases the capacitance to 10 pF. (a) What then is the potential of your body? That potential is reduced over time, as the charge on you drains through your body and shoes (you are a capacitor discharging through a resistance). Assume that the resistance along that route is 300 GΩ. If you touch an electrical component while your potential is greater than 100 V, you could ruin the component. (b) How long must you wait until your potential reaches the safe level of 100 V?

If you wear a conducting wrist strap that is connected to ground, your potential does not increase as much when you stand up; you also discharge more rapidly because the resistance through the grounding connection is much less than through your body and shoes. (c) Suppose that when you stand up, your potential is 1400 V and the chair-to-you capacitance is 10 pF. What resistance in that wrist-strap grounding connection will allow you to discharge to 100 V in 0.30 s, which is less time than you would need to reach for, say, your computer?

Answer:

(a) 3.0 kV; (b) 10 s; (c) 11 GΩ

In Fig. 27-72, the ideal batteries have emfs $\mathcal{E}_1 = 20.0$ V, $\mathcal{E}_2 = 10.0$ V, and $\mathcal{E}_3 = 5.00$ V, and the resistances are each 2.00 Ω. What are the (a) size and (b) direction (left or right) of current $i_1$? (c) Does battery 1 supply or absorb energy, and (d) what is its power? (e) Does battery 2 supply or absorb energy, and (f) what is its power? (g) Does battery 3 supply or absorb energy, and (h) what is its power?

A temperature-stable resistor is made by connecting a resistor made of silicon in series with one made of iron. If the required total resistance is 1000 Ω in a wide temperature range around 20°C, what should be the resistance of the (a) silicon resistor and (b) iron resistor? (See Table 26-1.)
Answer:

(a) 85.0Ω; (b) 915Ω

78 In Fig. 27-14, assume that $\mathcal{E} = 5.0$ V, $r = 2.0$ Ω, $R_1 = 5.0$ Ω, and $R_2 = 4.0$ Ω. If the ammeter resistance $R_A$ is 0.10 Ω, what percent error does it introduce into the measurement of the current? Assume that the voltmeter is not present.

79 **SSM** An initially uncharged capacitor $C$ is fully charged by a device of constant emf $\mathcal{E}$ connected in series with a resistor $R$. (a) Show that the final energy stored in the capacitor is half the energy supplied by the emf device. (b) By direct integration of $i^2R$ over the charging time, show that the thermal energy dissipated by the resistor is also half the energy supplied by the emf device.

80 In Fig. 27-73, $R_1 = 5.00$ Ω, $R_2 = 10.0$ Ω, $R_3 = 15.0$ Ω, $C_1 = 5.00 \mu$F, $C_2 = 10.0 \mu$F, and the ideal battery has emf $\mathcal{E} = 20.0$ V. Assuming that the circuit is in the steady state, what is the total energy stored in the two capacitors?

![Figure 27-73](Problem 80)

81 In Fig. 27-5a, find the potential difference across $R_2$ if $\mathcal{E} = 12$ V, $R_1 = 3.0$ Ω, $R_2 = 4.0$ Ω, and $R_3 = 5.0$ Ω.

**Answer:**

4.0 V

82 In Fig. 27-8a, calculate the potential difference between $a$ and $c$ by considering a path that contains $R$, $r_1$, and $\mathcal{E}_1$.

83 **SSM** A controller on an electronic arcade game consists of a variable resistor connected across the plates of a 0.220 μF capacitor. The capacitor is charged to 5.00 V, then discharged through the resistor. The time for the potential difference across the plates to decrease to 0.800 V is measured by a clock inside the game. If the range of discharge times that can be handled effectively is from 10.0 ms to 6.00 ms, what should be the (a) lower value and (b) higher value of the resistance range of the resistor?

**Answer:**

(a) 24.8Ω; (b) 14.9 kΩ

84 An automobile gasoline gauge is shown schematically in Fig. 27-74. The indicator (on the dashboard) has a resistance of 10 Ω. The tank unit is a float connected to a variable resistor whose resistance varies linearly with the volume of gasoline. The resistance is 140 Ω when the tank is
empty and 20 \( \Omega \) when the tank is full. Find the current in the circuit when the tank is (a) empty, (b) half-full, and (c) full. Treat the battery as ideal.

![Figure 27-74](image)

**Figure 27-74** Problem 84.

85 **SSM** The starting motor of a car is turning too slowly, and the mechanic has to decide whether to replace the motor, the cable, or the battery. The car's manual says that the 12 V battery should have no more than 0.020 \( \Omega \) internal resistance, the motor no more than 0.200 \( \Omega \) resistance, and the cable no more than 0.040 \( \Omega \) resistance. The mechanic turns on the motor and measures 11.4 V across the battery, 3.0 V across the cable, and a current of 50 A. Which part is defective?

**Answer:**

the cable

86 Two resistors \( R_1 \) and \( R_2 \) may be connected either in series or in parallel across an ideal battery with emf \( \mathcal{E} \). We desire the rate of energy dissipation of the parallel combination to be five times that of the series combination. If \( R_1 = 100 \Omega \), what are the (a) smaller and (b) larger of the two values of \( R_2 \) that result in that dissipation rate?

87 The circuit of Fig. 27-75 shows a capacitor, two ideal batteries, two resistors, and a switch S. Initially S has been open for a long time. If it is then closed for a long time, what is the change in the charge on the capacitor? Assume \( C = 10 \mu F \), \( \mathcal{E}_1 = 1.0 \) V, \( \mathcal{E}_2 = 3.0 \) V, \( R_1 = 0.20 \Omega \), and \( R_2 = 0.40 \Omega \).

![Figure 27-75](image)

**Figure 27-75** Problem 87.

**Answer:**

\(-13 \mu C\)

88 In Fig. 27-41, \( R_1 = 10.0 \Omega \), \( R_2 = 20.0 \Omega \), and the ideal batteries have emfs \( \mathcal{E}_1 = 20.0 \) V and \( \mathcal{E}_2 = 50.0 \) V. What value of \( R_3 \) results in no current through battery 1?

89 In Fig. 27-76, \( R = 10 \Omega \). What is the equivalent resistance between points A and B? (Hint: This
circuit section might look simpler if you first assume that points A and B are connected to a battery.)

![Diagram](image)

**Figure 27-76** Problem 89.

**Answer:**

20 Ω

90 (a) In Fig. 27-4a, show that the rate at which energy is dissipated in R as thermal energy is a maximum when \( R = r \). (b) Show that this maximum power is \( P = \frac{\mathcal{E}^2}{4r} \).

91 In Fig. 27-77, the ideal batteries have emfs \( \mathcal{E}_1 = 12.0 \) V and \( \mathcal{E}_2 = 4.00 \) V, and the resistances are each 4.00 Ω. What are the (a) size and (b) direction (up or down) of \( i_1 \) and the (c) size and (d) direction of \( i_2 \)? (e) Does battery 1 supply or absorb energy, and (f) what is its energy transfer rate? (g) Does battery 2 supply or absorb energy, and (h) what is its energy transfer rate?

![Diagram](image)

**Figure 27-77** Problem 91.

**Answer:**

(a) 3.00 A; (b) down; (c) 1.60 A; (d) down; (e) supply; (f) 55.2 W; (g) supply; (h) 6.40 W

92 Figure 27-78 shows a portion of a circuit through which there is a current \( I = 6.00 \) A. The resistances are \( R_1 = R_2 = 2.00R_3 = 2.00R_4 = 4.00 \) Ω. What is the current \( i_1 \) through resistor 1?
Problem 92.

Thermal energy is to be generated in a 0.10 $\Omega$ resistor at the rate of 10 W by connecting the resistor to a battery whose emf is 1.5 V. (a) What potential difference must exist across the resistor? (b) What must be the internal resistance of the battery?

Answer:

(a) 1.0 V; (b) 50 m$\Omega$

Problem 94.

Figure 27-79 shows three 20.0 resistors. Find the equivalent resistance between points (a) A and B, (b) A and C, and (c) B and C. (Hint: Imagine that a battery is connected between a given pair of points.)

Problem 95.

A 120 V power line is protected by a 15 A fuse. What is the maximum number of 500 W lamps that can be simultaneously operated in parallel on this line without “blowing” the fuse because of an excess of current?

Answer:

3

Problem 96.

Figure 27-63 shows an ideal battery of emf $\varepsilon = 12$ V, a resistor of resistance $R = 4.0 \, \Omega$, and an uncharged capacitor of capacitance $C = 4.0 \, \mu F$. After switch S is closed, what is the current through the resistor when the charge on the capacitor is 8.0 $\mu C$?

Problem 97.

SSM A group of $N$ identical batteries of emf $\varepsilon$ and internal resistance $r$ may be connected all in series (Fig. 27-80a) or all in parallel (Fig. 27-80b) and then across a resistor $R$. Show that both arrangements give the same current in $R$ if $R = r$. 

Figure 27-78

Figure 27-79

Figure 27-80
In Fig. 27-48, $R_1 = R_2 = 10.0 \, \Omega$, and the ideal battery has emf $\mathcal{E} = 12.0 \, \text{V}$. (a) What value of $R_3$ maximizes the rate at which the battery supplies energy and (b) what is that maximum rate?

In Fig. 27-66, the ideal battery has emf $\mathcal{E} = 30 \, \text{V}$, the resistances are $R_1 = 20 \, \text{k} \, \Omega$ and $R_2 = 10 \, \text{k} \, \Omega$, and the capacitor is uncharged. When the switch is closed at time $t = 0$, what is the current in (a) resistance 1 and (b) resistance 2? (c) A long time later, what is the current in resistance 2?

**Answer:**

(a) 1.5 mA; (b) 0; (c) 1.0 mA