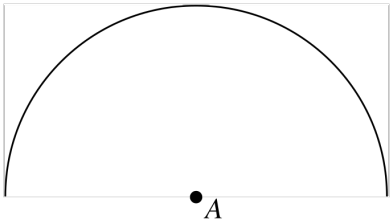
PHYSICS C: ELECTRICITY AND MAGNETISM
SECTION I
Time—45 minutes
35 Questions

Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

Note: To simplify calculations, you may use $g = 10$ m/s^2 in all problems.

1. A uniformly charged, nonconducting sphere is held at a fixed position. When a **proton** is outside the sphere at a distance D from the center of the sphere, the magnitude of the acceleration of the proton is a. If an **electron** is at a distance $2D$ from the center of the same sphere, what is the magnitude of the acceleration of the electron in terms of a?

   (A) $\frac{1833}{a}$
   (B) $\frac{a}{4}$
   (C) $458a$
   (D) $917a$
   (E) $1833a$



2. A nonconducting rod of charged material has a uniform positive charge density $+\lambda$. The rod is formed into a semicircle with point A at its center, as shown in the figure above. What is the direction of the electric field at point A?

   (A)
   (B)
   (C)
   (D)
   (E) There is no direction because the electric field is zero.

3. A student who is holding a charged plastic rod walks at a constant velocity past a stationary student. The stationary student is holding sensors that are capable of detecting electric and magnetic fields. Which of the following should the stationary student expect to detect?

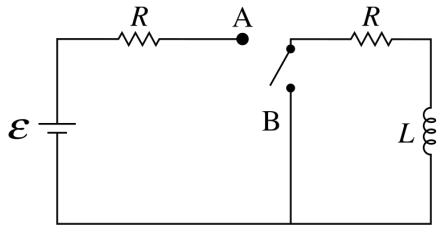
   (A) A changing magnetic field only, because moving charges only create magnetic fields

   (B) A constant electric field only, because the charge on the plastic rod is constant

   (C) A changing electric field only, because the distance between the plastic rod and the sensors is changing

   (D) Both a constant magnetic field and a constant electric field, because the charge on the plastic rod and the velocity of the plastic rod are constant

   (E) Both a changing magnetic field and a changing electric field, because the distance between the plastic rod and the sensors is changing



4. A circuit has two identical resistors, each with resistance R, a battery, and an inductor with inductance L, as shown. The switch is initially open and then switched to position A. It takes time t_A for the current in the inductor to reach 63% of the steady-state current I_s. After a long time, the switch is moved to position B, and it takes time t_B for the current in the inductor to reach 37% of I_s. The ratio $\frac{t_A}{t_B}$ is equal to

   (A) 0.50

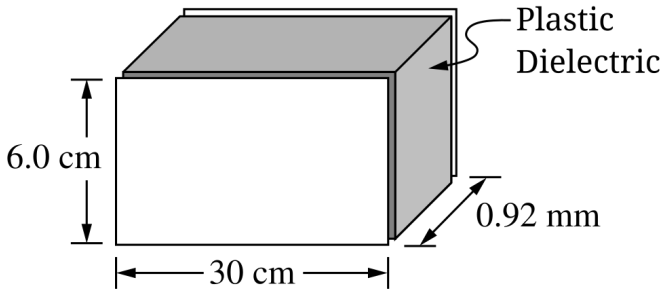
   (B) 0.60

   (C) 1.0

   (D) 1.6

   (E) 2.0

Questions 5-6



Note: Figure not drawn to scale.

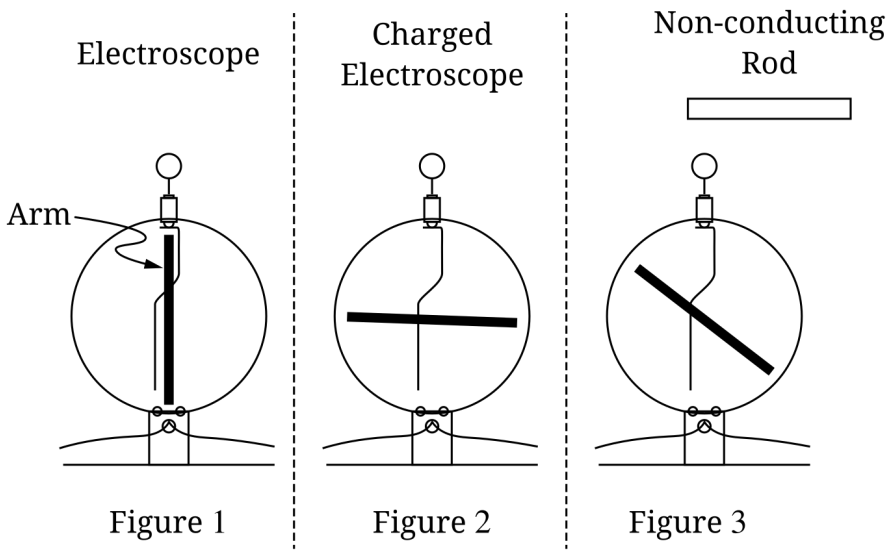
An 830 pF parallel-plate capacitor has plates of length 6.0 cm and width 30 cm. The plates are 0.92 mm apart, as shown. There is a plastic dielectric that fills the space between the plates.

5. What is the value of the dielectric constant of the plastic dielectric?

   (A) 1835
   (B) 19.6
   (C) 4.8
   (D) 0.05
   (E) 4.2×10^{-11}

6. The capacitor is connected to a battery and allowed to reach equilibrium. A charge of magnitude Q is on each of the capacitor's plates. The same battery is then connected to a new capacitor with identical dimensions but with a dielectric that has three times the dielectric constant of the original. When equilibrium is reached, what is the magnitude of the charge on one plate of the new capacitor?

   (A) $\frac{1}{9}Q$
   (B) $\frac{1}{3}Q$
   (C) Q
   (D) $3Q$
   (E) $9Q$



7. The arm of a neutral electroscope is vertical, as shown in Figure 1. The electroscope is given a charge, and the arm moves to the position shown in Figure 2. Then a uniformly charged non-conducting rod is brought near the top of the electroscope, and the arm of the electroscope moves to the position shown in Figure 3. Which of the following must be true about the charge on the electroscope and the rod?

   (A) Both the electroscope and the rod are positively charged.

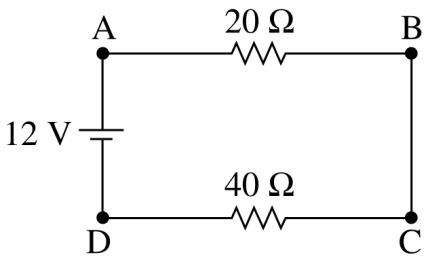
   (B) Both the electroscope and the rod are negatively charged.

   (C) The electroscope is positively charged, and the rod is negatively charged.

   (D) The electroscope is negatively charged, and the rod is positively charged.

   (E) The electroscope and the rod have opposite types of charge, but it cannot be determined which is positively charged and which is negatively charged.

Questions 8-9



A battery and two resistors are connected in series, as shown. Four points in the circuit are labeled A, B, C, and D.

8. Which of the following is true of the absolute value of the potential difference between points A and B ?

   (A) It is less than that between C and D.

   (B) It is the same as that between C and D.

   (C) It is greater than that between C and D.

   (D) It is the same as that between D and A.

   (E) It is greater than that between D and A.

9. If the amount of energy dissipated each second by the 20 Ω resistor is E, what is the energy dissipated each second by the 40 Ω resistor and why?

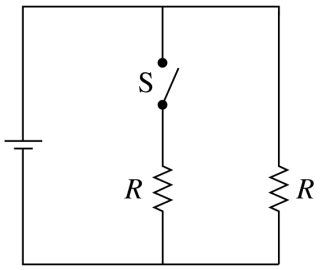
   (A) $4E$, because the currents through the resistors are the same

   (B) $2E$, because the currents through the resistors are the same

   (C) E, because the currents through the resistors are the same and the potential differences across the resistors are the same

   (D) $2E$, because the potential differences across the resistors are the same

   (E) $4E$, because the potential differences across the resistors are the same



10. In the circuit shown above, the two resistors are identical and the battery has negligible internal resistance. Before the switch S is closed, the battery delivers a current I and a power P. After the switch is closed, what are the current and power delivered by the battery?

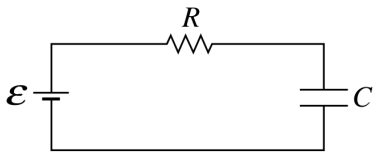
    (A) The current is $2I$ and the power is $2P$.

    (B) The current is $2I$ and the power is $\frac{1}{2}P$.

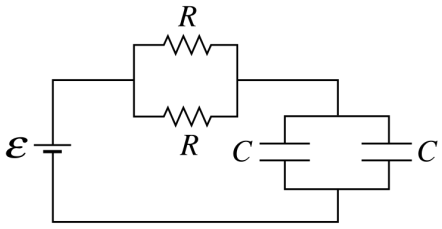
    (C) The current is I and the power is P.

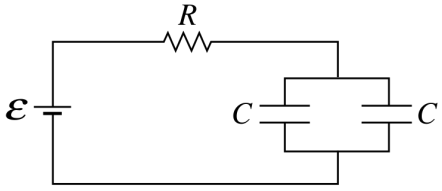
    (D) The current is I and the power is $2P$.

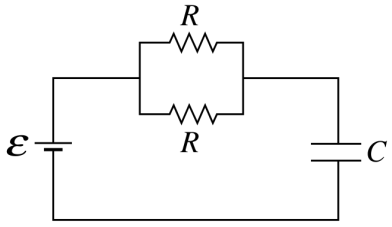
    (E) The current is $\frac{1}{2}I$ and the power is P.

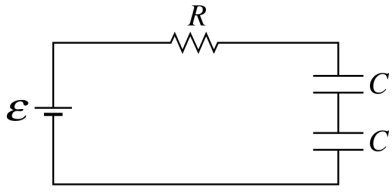


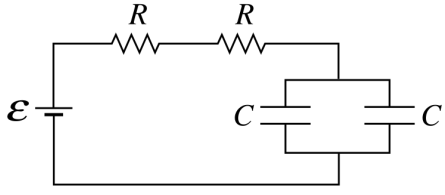
11. In the circuits shown above, all resistors have the same resistance R and all capacitors have the same capacitance C. Which of the following circuits will have the same time constant as the circuit shown in the figure above?

(A)


(B)


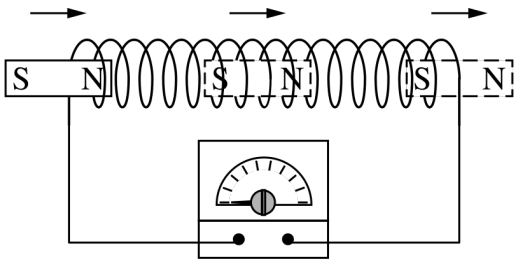
(C)


(D)


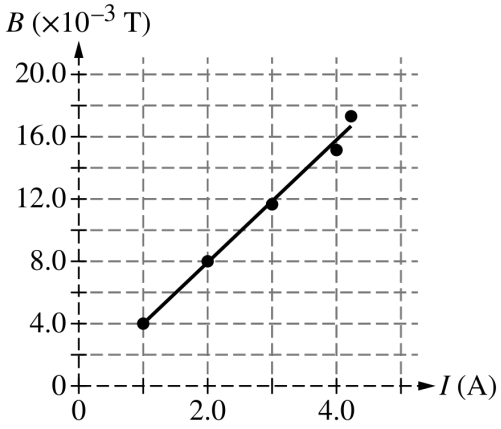
(E)


Questions 12-13

Students are to perform an experiment using a 15 cm long solenoid, a magnetic field probe, a bar magnet, a power supply, connecting wires, and meters for collecting voltage and current data.



Note: Figure not drawn to scale.



12. The students disconnect the solenoid from the power supply and connect the solenoid to the voltmeter. They move the bar magnet into, through, and out of the solenoid at constant speed, as shown. The length of the bar magnet is much smaller than the length of the solenoid. When will the voltmeter detect an emf?

    I. When the bar magnet is entering the solenoid

    II. When the bar magnet is moving through the center of the solenoid

    III. When the bar magnet is leaving the solenoid

    (A) I only

    (B) III only

    (C) I and II

    (D) I and III

    (E) II and III

13. The students insert the magnetic field probe along the axis of the solenoid at the midpoint of the solenoid. The solenoid is connected to the power supply, and measurements are recorded for the magnitude B of the magnetic field at that location as a function of the current I passing through it. The data are taken for five different power supply settings, and the plot of the data is shown in the graph. Which of the following is correct for the total number of loops for this solenoid?

    (A) 3200

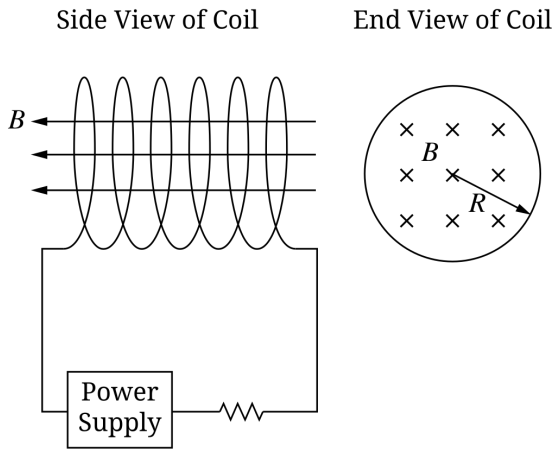
    (B) 480

    (C) 250

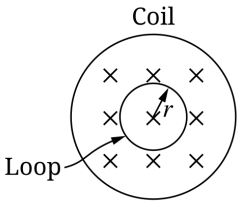
    (D) 60

    (E) The number of loops cannot be determined without knowing the radius of the solenoid.

Questions 14-15



A coil of wire of radius $R = 10$ cm is connected to a variable power supply and a resistor, as shown. The power supply is initially off. At time $t = 0$, the power supply is set to a nonzero voltage and turned on. As a result, a uniform magnetic field with magnitude B is created inside the coil.



14. A loop of wire of radius $r = 5$ cm and resistance $R_L = 2\ \Omega$ is inserted into the coil, as shown above. The power supply is adjusted so that the magnitude of the magnetic field B in the coil as a function of time t is $B(t) = \beta + \alpha t$, where $\beta = 25\ \mu$T and $\alpha = 12\ \mu$T/s. The current induced in the loop is most nearly

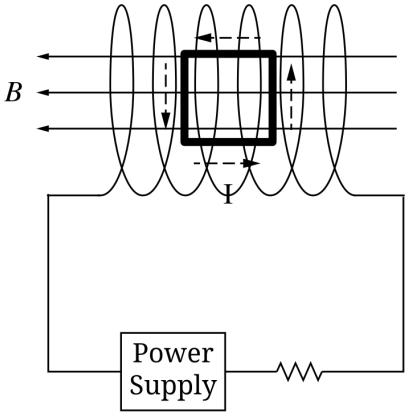
    (A) 3.7×10^{-6} A

    (B) 2.0×10^{-6} A

    (C) 5.2×10^{-7} A

    (D) 1.9×10^{-7} A

    (E) 4.7×10^{-8} A



15. A rectangular loop of wire with a counterclockwise current is inserted into the coil, as shown above, and released. Which of the following best describes the resulting motion of the loop?

    (A) It will not rotate.

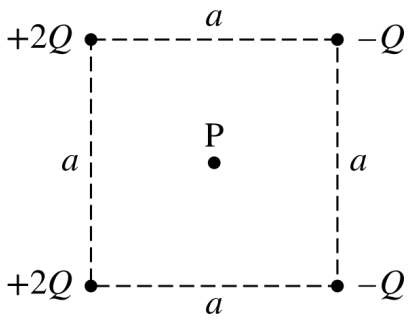
    (B) It will rotate clockwise in the plane of the page.

    (C) It will rotate counterclockwise in the plane of the page.

    (D) It will rotate such that the right side of the loop will rotate out of the page.

    (E) It will rotate such that the right side of the loop will rotate into the page.

Questions 16-17



Four point charges are located at the corners of a square of side a, as shown in the figure above. Point P is at the center of the square.

16. Which of the following best represents the direction of the electric field at point P?

(A) 

(B)

(C)

(D) 

(E)

17. What is the electric potential V at point P?

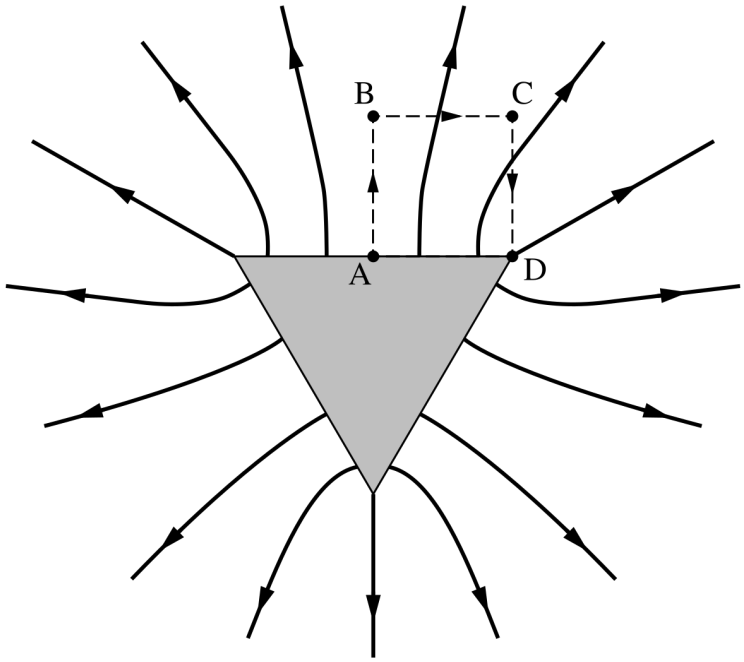
(A) $V = \dfrac{2Q}{\sqrt{2}\pi\varepsilon_0 a}$

(B) $V = \dfrac{Q}{\sqrt{2}\pi\varepsilon_0 a}$

(C) $V = \dfrac{Q}{2\sqrt{2}\pi\varepsilon_0 a}$

(D) $V = \dfrac{Q}{4\sqrt{2}\pi\varepsilon_0 a}$

(E) $V = 0$



18. The diagram shows the electric field near a charged metallic triangular plate. The dashed lines are paths of equal length along which an integral may be evaluated. Integrating the electric field along a certain path can provide information about the changes in electric potential along the path. Which of the following equations correctly relates integrals along the paths AB, BC, and CD?

(A) $\int_A^B \vec{E}\cdot d\vec{r} + \int_B^C \vec{E}\cdot d\vec{r} - \int_C^D \vec{E}\cdot d\vec{r} = 0$

(B) $\int_A^B \vec{E}\cdot d\vec{r} + \int_B^C \vec{E}\cdot d\vec{r} - \int_C^D \vec{E}\cdot d\vec{r} > 0$

(C) $\int_A^B \vec{E}\cdot d\vec{r} + \int_B^C \vec{E}\cdot d\vec{r} + \int_C^D \vec{E}\cdot d\vec{r} = 0$

(D) $\int_A^B \vec{E}\cdot d\vec{r} + \int_B^C \vec{E}\cdot d\vec{r} + \int_C^D \vec{E}\cdot d\vec{r} < 0$

(E) $\int_A^B \vec{E}\cdot d\vec{r} - \int_B^C \vec{E}\cdot d\vec{r} - \int_C^D \vec{E}\cdot d\vec{r} = 0$

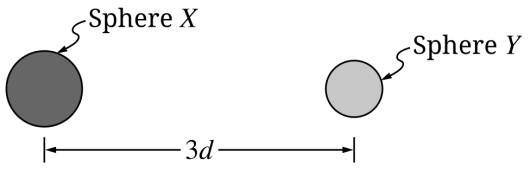


Figure I

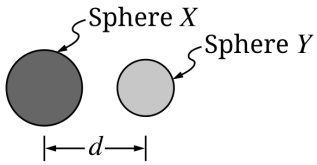


Figure II

Note: Figure not drawn to scale.

19. Nonconducting Sphere X is fixed in place and has a charge $+Q$. Conducting Sphere Y is electrically neutral and starts at a distance $3d$ away from Sphere X, as indicated in Figure I above. Sphere Y is then brought toward Sphere X to a new position d away from Sphere X, as indicated in Figure II above. Which of the following is true of the electric force on Sphere Y from Sphere X and the electric potential energy of the two-sphere system as Sphere Y is brought toward Sphere X?

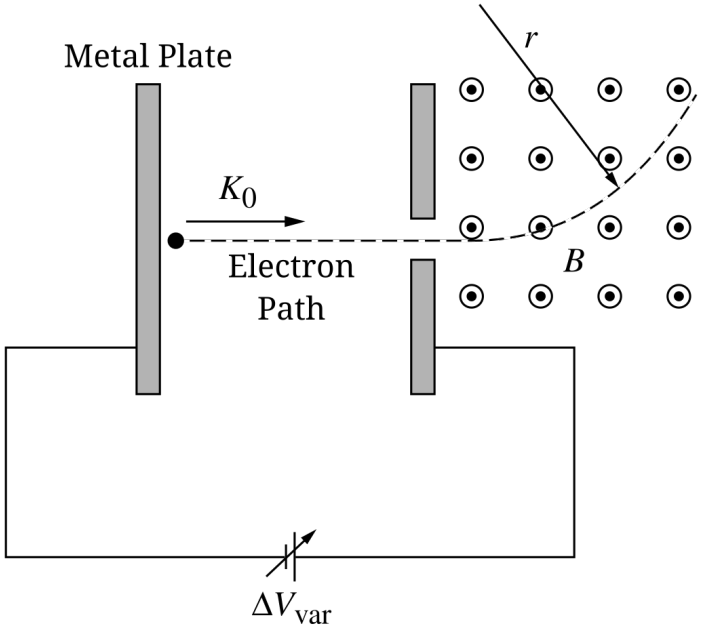
(A) The electric force on Y is attractive and the electric potential energy decreases.

(B) The electric force on Y is attractive and the electric potential energy increases.

(C) The electric force on Y is repulsive and the electric potential energy decreases.

(D) The electric force on Y is repulsive and the electric potential energy increases.

(E) The electric force on Y is nonexistent and the electric potential energy remains the same.



20. An electron is emitted from a metal plate with an initial nonzero kinetic energy K_0. The electron is accelerated to the right by a variable voltage ΔV_{var} and then deflected by a magnetic field B through a circular arc of radius r as shown in the figure. The potential difference ΔV_{var} that needs to be applied for the electron to be deflected through a circular path of radius r is

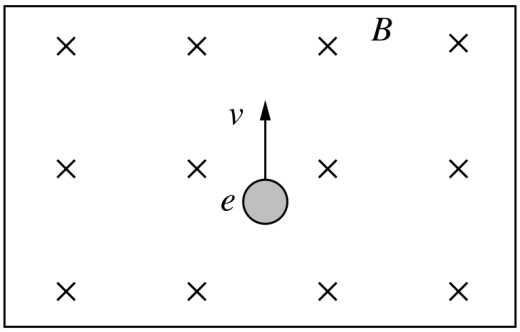
(A) $\dfrac{eB^2r^2}{2m_e}$

(B) $\dfrac{eB^2r^2}{2m_e} - \dfrac{K_0}{e}$

(C) $\dfrac{eB^2r^2}{2m_e} + \dfrac{K_0}{e}$

(D) $\dfrac{eB^2r^2}{2m_e} - \dfrac{K_0}{2e}$

(E) $\dfrac{eB^2r^2}{2m_e} - \dfrac{K_0}{2e}$



21. The figure shows a uniform magnetic field, B, directed into the page. At the instant shown, an electron of mass me is moving with velocity v perpendicular to the field, toward the top of the page. As a result of this motion, the electron moves in a circular path. Which of the following gives an expression for the radius of the path and the direction of circular motion?

(A) The radius is $\frac{m_e v}{eB}$ and the direction is clockwise.

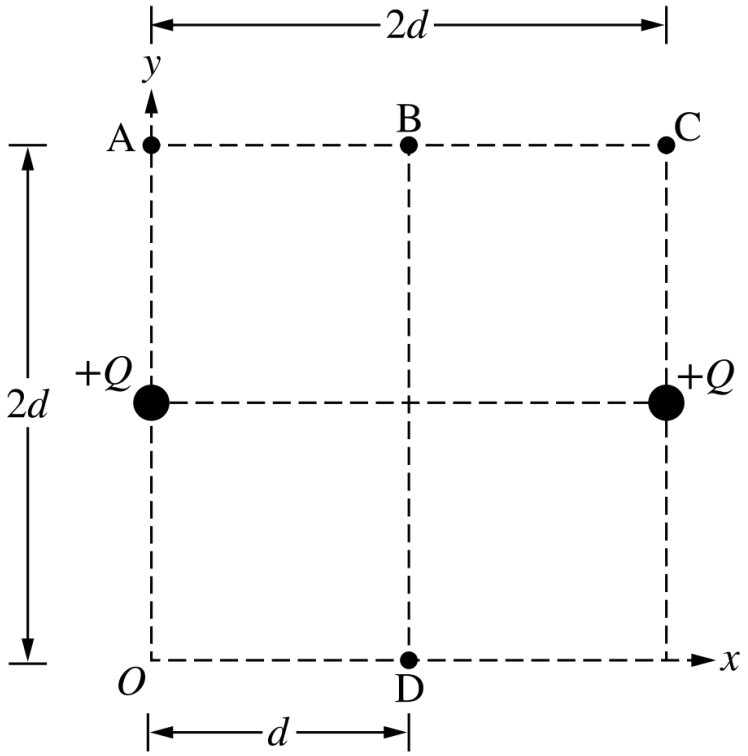
(B) The radius is $\frac{m_e v}{eB}$ and the direction is counterclockwise.

(C) The radius is $\frac{m_e v^2}{eB}$ and the direction is clockwise.

(D) The radius is $\frac{m_e v^2}{eB}$ and the direction is counterclockwise.

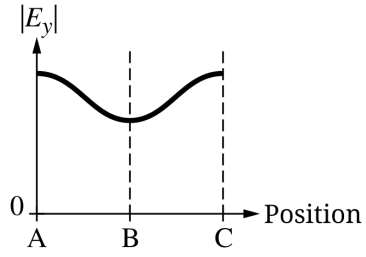
(E) The radius is $\frac{eB}{m_e v}$ and the direction is counterclockwise.

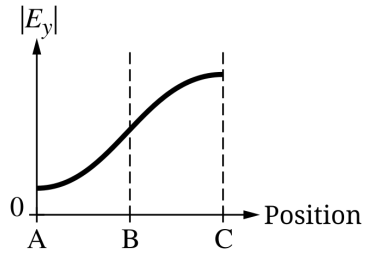
Questions 22-23

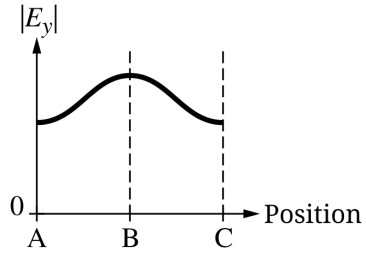


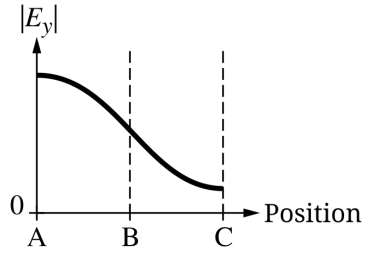
Two spheres with charge $+Q$ are positioned a distance $2d$ apart, as shown. Points A, B, C, and D are labeled. The dashed line connecting B to D bisects the line joining the two spheres.

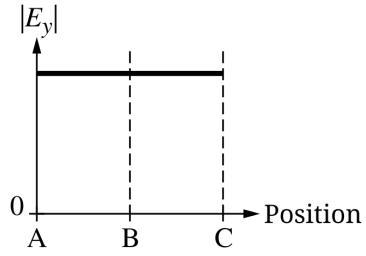
22. Which of the following graphs best represents the magnitude of the y-component of the net electric field $|E_y|$ as a function of position along a straight horizontal path from point A to point C?

(A)


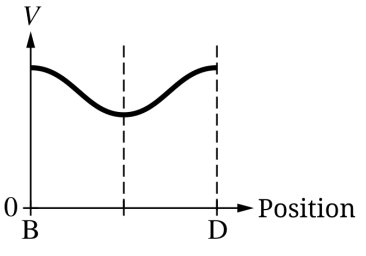
(B)


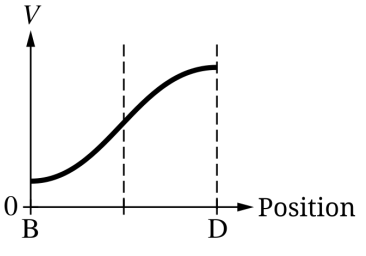
(C)


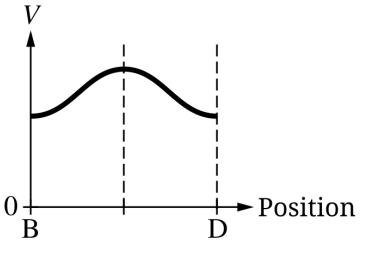
(D)


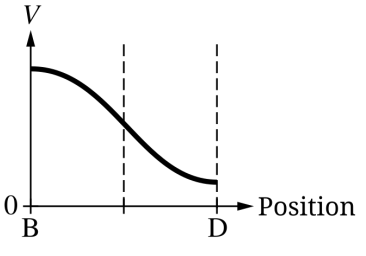
(E)


23. Which of the following graphs best represents the net electric potential V as a function of position along a straight path from point B to point D?

(A)


(B)


(C)


(D)


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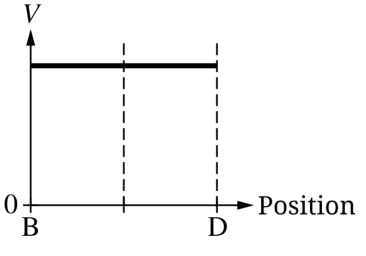
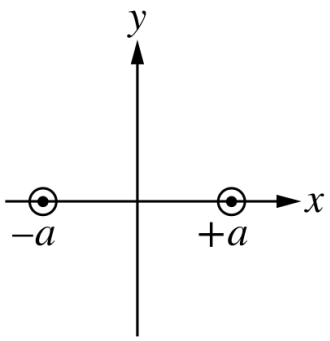
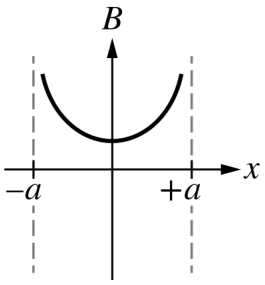
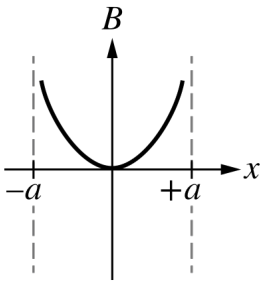
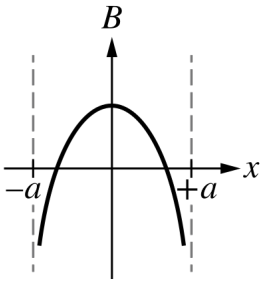




24. Two wires carrying equal currents of magnitude I perpendicularly out of the plane of the page are fixed on the x-axis at $x = \pm a$, as shown above. Which of the following graphs best shows the total magnetic field B as a function of position on the x-axis between $-a$ and $+a$, assuming that the field is positive when in the $+y$ direction?

(A)


(B)


(C)


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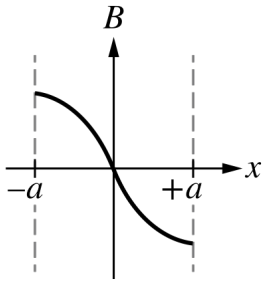
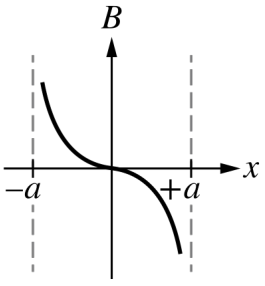


(E)


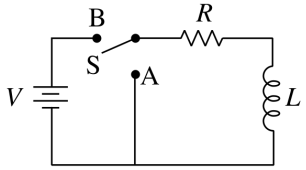


Figure 1

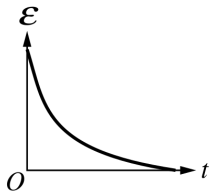


Figure 2

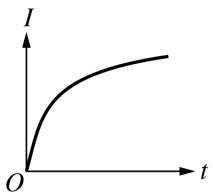


Figure 3

25. Inductor L, resistor R, and switch S are connected to an ideal battery V, as shown in Figure 1. Switch S can be closed to either position A or B. Figure 2 above shows a graph of the magnitude of the emf ε across the inductor as a function of time t. Figure 3 above shows a graph of the magnitude of the current I in the inductor as a function of time t. For which of the following situations would these graphs be valid representations?

I. The switch has been in position A for a long time and is moved to position B at time $t = 0$.

II. The switch has been in position B for a long time and is moved to position A at time $t = 0$.

III. The switch has been open for a long time and is moved to position B at time $t = 0$.

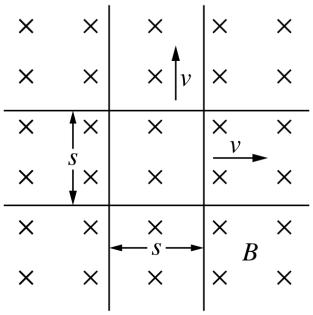
(A) I only

(B) II only

(C) III only

(D) I and III only

(E) I, II, and III



26. Two pairs of long, parallel wires are arranged to produce a conducting square, as shown. A uniform, constant magnetic field is directed into the page throughout the region. The top horizontal wire is moving toward the top of the page with speed v and the right vertical wire is moving to the right with speed v such that the side length increases at a constant rate, inducing an emf in the square loop. At the instant shown, the side length is s and the emf induced in the loop is ε. What is the emf induced in the loop when the sides of the square have length $2s$?

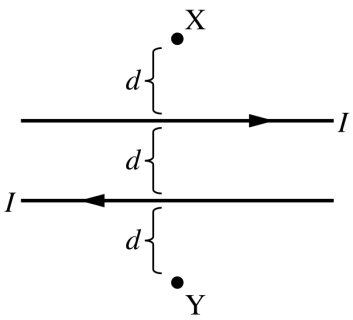
(A) $\frac{\varepsilon}{4}$

(B) $\frac{\varepsilon}{2}$

(C) ε

(D) 2ε

(E) 4ε



27. Two parallel current-carrying wires are in the same plane as points X and Y. The magnetic fields due to the wires at points X and Y are B_X and B_Y, respectively. How do B_X and B_Y compare in magnitude and direction?

(A) Equal magnitudes, same direction

(B) Equal magnitudes, opposite directions

(C) Each has a magnitude of zero, no direction

(D) Different magnitudes, same direction

(E) Different magnitudes, opposite directions

28. Two long, parallel wires 30 cm apart carry currents in the same direction. Wire R has a current of 4 A, and Wire S has a current of 8 A. In the plane of the wires, how far from Wire R is the net magnetic field zero?

(A) 10 cm

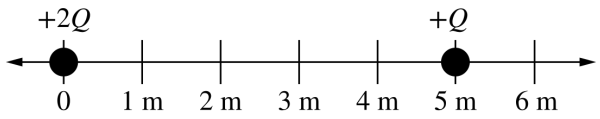
(B) 15 cm

(C) 20 cm

(D) 25 cm

(E) There is no position between the wires where the net magnetic field is zero.

Questions 29-30



A pair of charged particles having charges $+2Q$ and $+Q$ are arranged along a line, as shown in the figure above.

29. At which of the labeled positions is the electric potential highest?

    (A) 1 m
    (B) 2 m
    (C) 3 m
    (D) 4 m
    (E) 6 m

30. Which of the following identifies the labeled position where the electric field is closest to zero and explains why?

    (A) 2 m, because the electric field is inversely proportional to charge and inversely proportional to distance.
    (B) 3 m, because the electric field is directly proportional to charge and inversely proportional to distance.
    (C) 3 m, because the electric field is directly proportional to charge and inversely proportional to the square of distance.
    (D) 4 m, because the electric field is directly proportional to charge and inversely proportional to distance.
    (E) 4 m, because the electric field is directly proportional to charge and inversely proportional to the square of distance.

31. Three resistors of resistance 8.0 Ω, 12 Ω, and 24 Ω are connected in parallel to a battery. The current through the battery is 20 A. What is the potential difference across this combination of resistors?

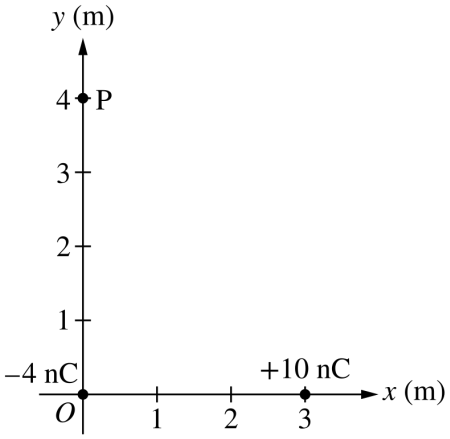
(A) 0.45 V

(B) 3.0 V

(C) 4.0 V

(D) 5.0 V

(E) 80 V



32. What is the electric potential at location P due to the two point charges located along the x-axis as shown?

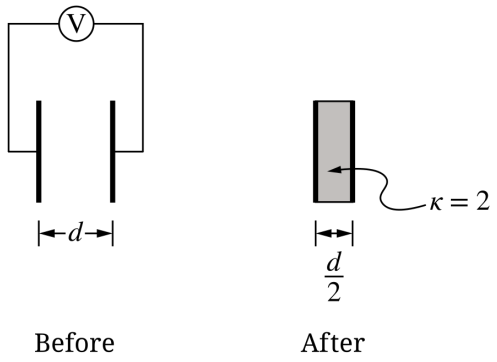
(A) -9.0^{-5} V

(B) 1.35 V

(C) 5.85 V

(D) 9.00 V

(E) 27.0 V



33. An isolated, air-filled parallel plate capacitor consists of two metal plates, each of area A, separated by a distance d with a potential difference V between the plates. The capacitor is disconnected from the battery. The separation is reduced to a distance of $\frac{d}{2}$, and a dielectric material of $\kappa = 2$ is inserted between the plates. What is the electric potential difference of the capacitor after the changes have been made?

(A) V
(B) $2V$
(C) $\frac{V}{2}$
(D) $4V$
(E) $\frac{V}{4}$

34. The current in a 10 Ω resistor is given as a function of time t by the equation $I = I_0 e^{\alpha t}$, where $I_0 = 4$ A and $\alpha = 2\text{s}^{-1}$. Which of the following represents the rate of energy dissipation in the resistor at time $t = 3$ s?

(A) $20e^{-6}$ W
(B) $40e^{-6}$ W
(C) $160e^{-6}$ W
(D) $40e^{-12}$ W
(E) $160e^{-12}$ W

Figure 1

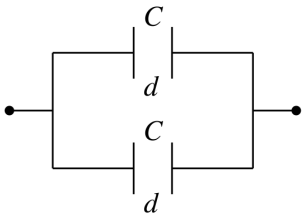
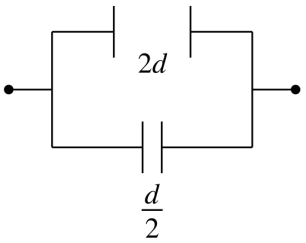


Figure 2



35. Two identical parallel-plate capacitors are connected in parallel, as shown in Figure 1. Both capacitors have plates that are a distance d apart and each has a capacitance C. The distance between the plates of the upper capacitor is increased to $2d$ and the distance between the plates of the lower capacitor is decreased to $\frac{d}{2}$, as shown in Figure 2. The equivalent capacitance of the two capacitors in Figure 2 is

(A) $\frac{5}{2}C$
(B) $2C$
(C) $\frac{3}{2}C$
(D) C
(E) $\frac{1}{2}C$

STOP
END OF ELECTRICITY AND MAGNETISM SECTION I

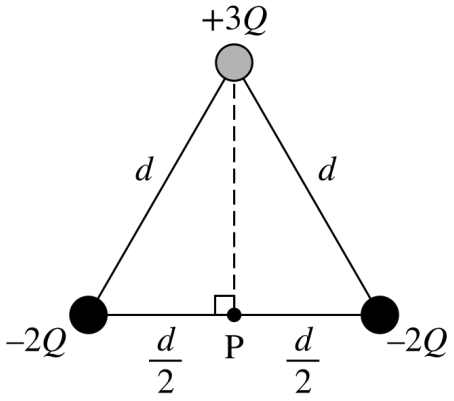
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

Time—45 minutes

3 Questions

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

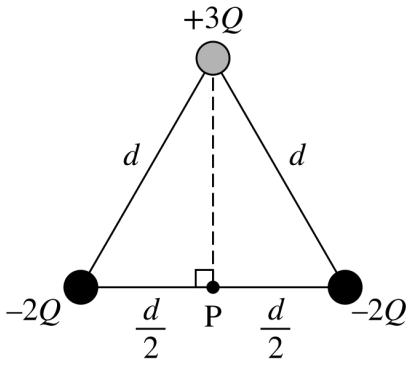


1. Three point charges are brought from very far away and placed at the corners of an equilateral triangle with sides of length d. The top point charge has a charge of $+3Q$, and each of the point charges located on the base of the triangle has a charge of $-2Q$. Point P is located at the midpoint of the base of the triangle, as shown. Express all algebraic answers in terms of Q, d, and physical constants, as appropriate.

   (a) Derive an expression for the work required to assemble the charges in the configuration shown.

   (b) Derive an expression for the magnitude of the electric field at Point P.

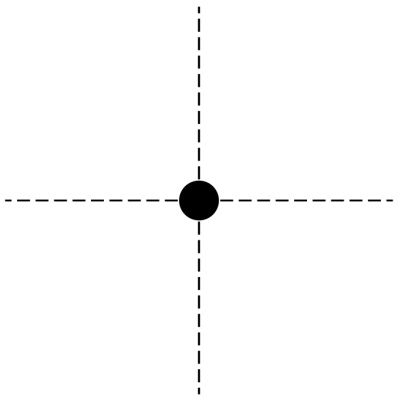
   (c) On the following charge configuration, draw a Gaussian surface that would have the maximum amount of net electric flux enter or exit its surface.



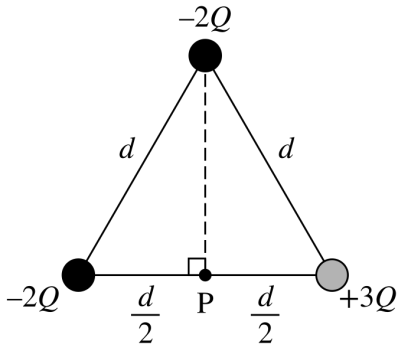
(d) Derive an expression for the electric potential at Point P.

(e) A positive test charge q is placed at Point P.

i. On the following diagram, draw an arrow to indicate the direction of the net force exerted on the test charge. The arrow should start on, and point away from, the dot.



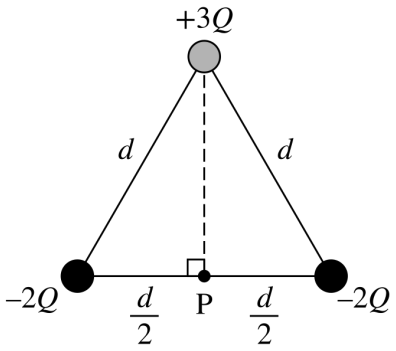
ii. The locations of the point charges at the top and bottom right corner of the triangle are switched, as shown in the following diagram.



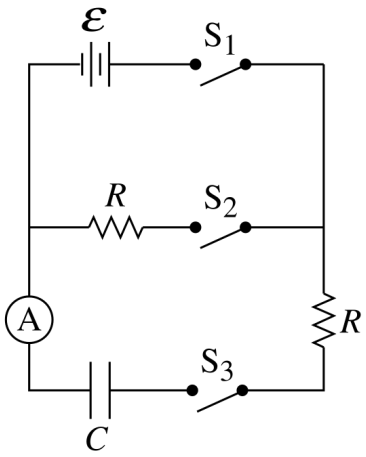
Does the direction of the net force on the test charge change? If the direction changes, indicate the direction of the new net force, and justify your answer. If the direction does not change, justify your answer.

(f) The charges are returned to their initial positions.

i. On the following diagram, put an "x" at a location where an additional negative charge could be placed so the net force on the $+3Q$ charge would be zero.



ii. Explain your reasoning for the location indicated in part (f)(i).

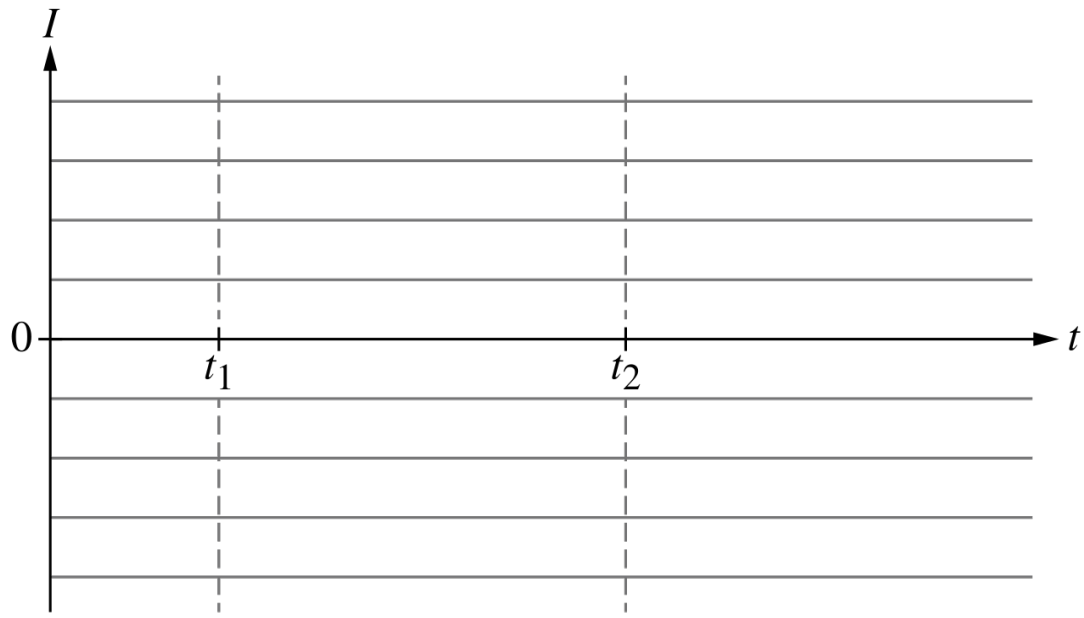


2. In a laboratory, a group of students constructs the circuit shown in Figure 1. The circuit includes a power supply, two identical resistors, a capacitor, three switches, and an ammeter. Initially, all switches are open and the capacitor is uncharged.

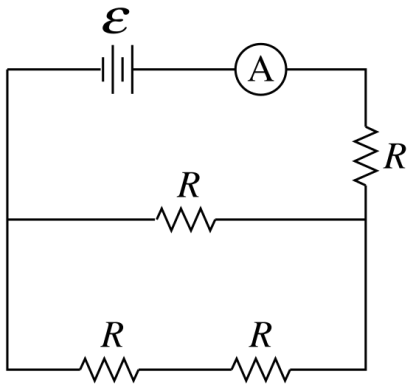
   The students perform the following procedure.

   - At time $t = 0$, Switch S_3 is closed.
   - At time $t = t_1$, Switch S_1 is also closed. The students wait a long time for the circuit to reach steady state.
   - At time $t = t_2$, S_1 is opened and Switch S_2 is closed simultaneously. S_3 remains closed.

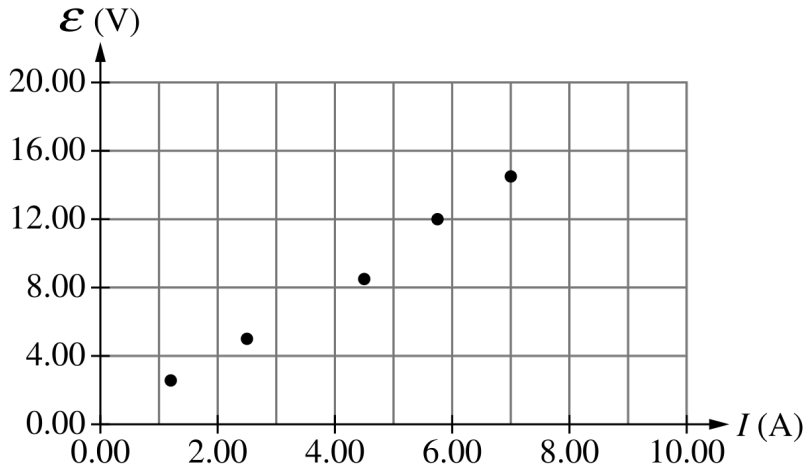
   (a) On the following axes, sketch a graph of the current I measured by the ammeter as a function of time t, from time $t = 0$ to a long time after t_2. Consider positive direction of current in the ammeter to be toward the top of the page.



The students then construct the following circuit.



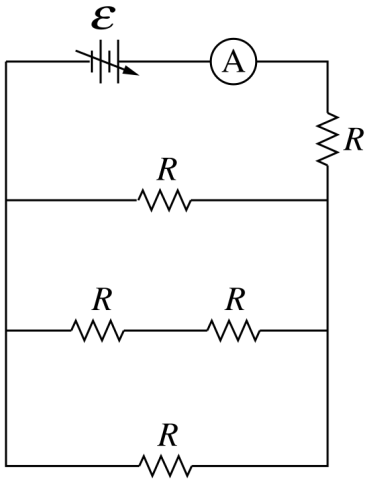
(b) The circuit includes a variable power supply, four identical resistors, and an ammeter, as shown in Figure 2. The power supply is set to various potential differences ε, and the ammeter measures current I. The data plotted by the students are shown in the following graph.



i. Draw a line that represents the best fit to the data points shown.

ii. Use the best-fit line to calculate the experimental value for the resistance R of one of the resistors.

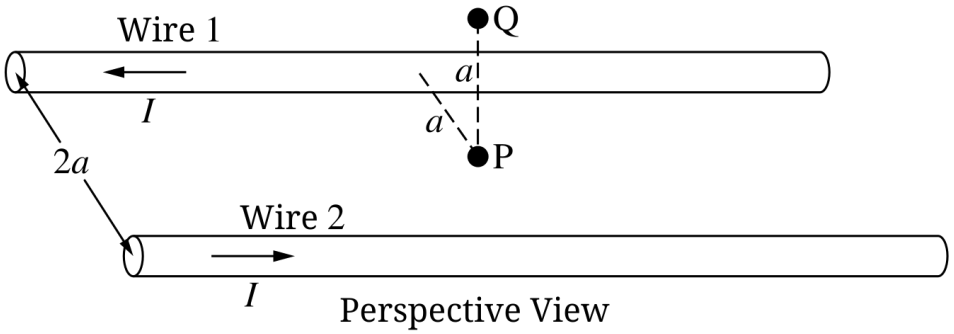
iii. The power supply is set to 20 V. For a time interval of 3 seconds, calculate the energy dissipated by the resistor at the bottom left of the circuit in Figure 2.



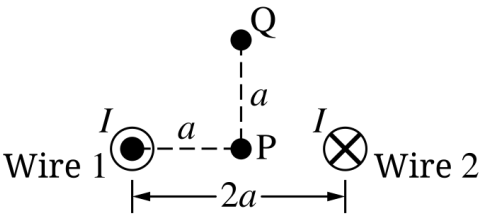
(c) The students add another identical resistor to the circuit, as shown in Figure 3. The experiment is repeated, and the students plot their new data. Would the slope of the new graph be greater than, less than, or equal to the slope of the graph in part (b)?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.



Perspective View

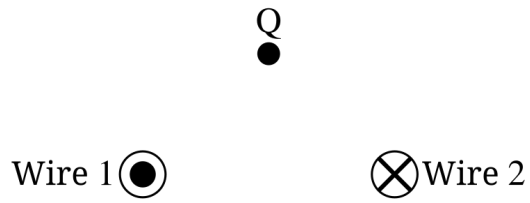


Cross-Sectional View

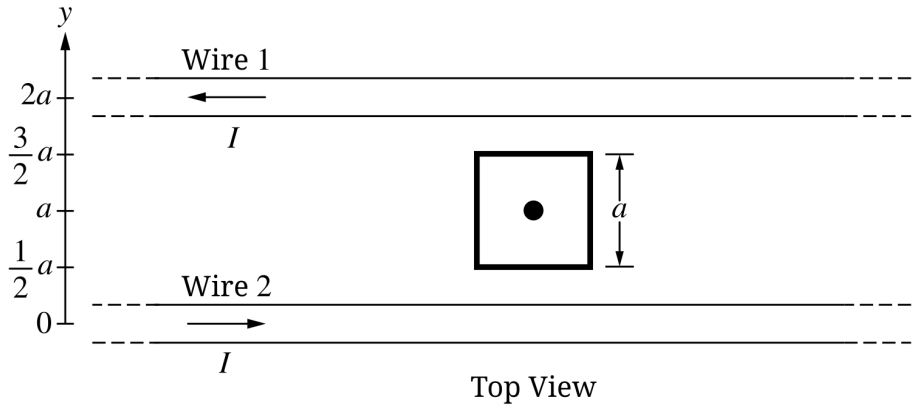
Note: Figure not drawn to scale.

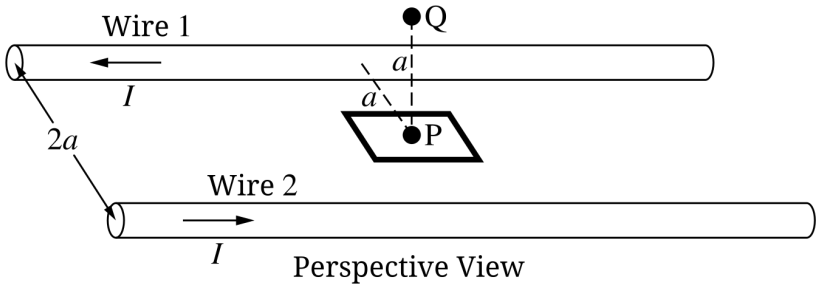
3. A pair of long parallel conducting wires labeled Wire 1 and Wire 2 lie in a horizontal plane with their centers located a distance $2a$ apart. Point P is located midway between the two wires and Point Q is a distance a directly above Point P, as shown in the perspective view. Power supplies deliver constant current I to both wires, with the direction of the current out of the page in Wire 1 and into the page in Wire 2, as shown in the cross-sectional view.

(a) i. On the following diagram, draw an Amperian loop that could be used to find the magnitude of the magnetic field due to Wire 2 at Point Q.



ii. Using Ampere's law, derive an expression for the magnitude of the magnetic field B_2 at Point Q due to Wire 2. Express your answer in terms of I, a, and physical constants, as appropriate.

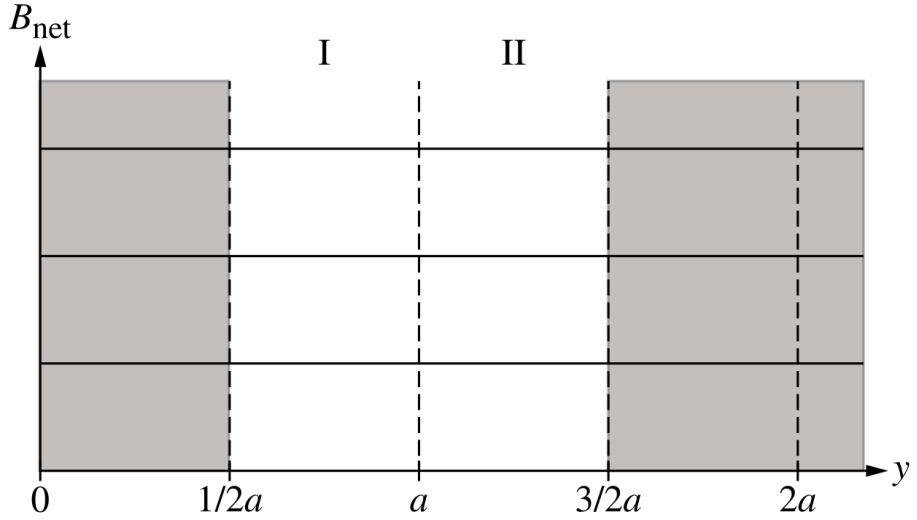




Note: Figure not drawn to scale.

(b) A square loop of wire with nonnegligible resistance is placed in the same plane as Wire 1 and Wire 2. The square loop has sides of length a and is centered about Point P. The bottom edge of the square loop is parallel to the wires, as shown.

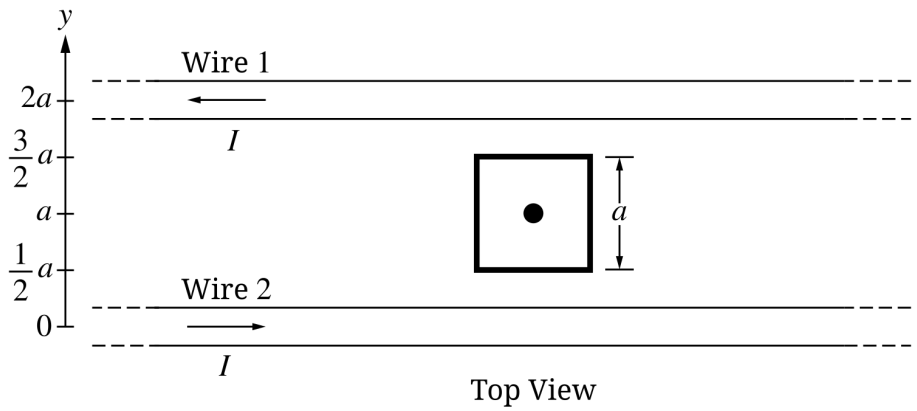
i. In regions I and II on the following axes, sketch a graph of the magnitude of the net magnetic field B_{net} as a function of y.



ii. Derive an expression for the total magnetic flux passing through the square loop in terms of I, a, and physical constants as appropriate.

(c) The power supplies connected to Wire 1 and Wire 2 are now turned off. At time $t = 0$ the power supplies are turned back on, and the current in Wire 1 and Wire 2 increases at a constant rate until steady state currents are reached at $t = t_1$. After $t = t_1$, the current in Wire 1 and Wire 2 remains at steady state.

i. For the time interval $t = 0$ to $t = t_1$, is the induced current in the square loop (as shown in the top view) clockwise, counterclockwise, or zero?
_____ Clockwise _____ Counterclockwise _____ Zero
Briefly justify your answer.

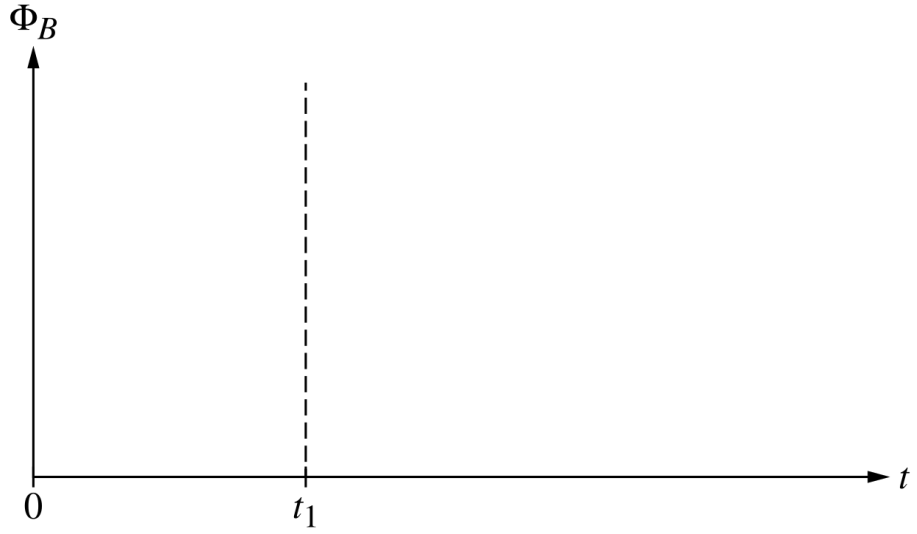


Top View

Note: Figure not drawn to scale.

ii. After time $t = t_1$, is the induced current in the square loop (as shown in the top view) clockwise, counterclockwise or zero?
_____ Clockwise _____ Counterclockwise _____ Zero
Briefly justify your answer.

iii. On the following axes, sketch a graph of the magnitude of the magnetic flux Φ_B through the square loop from Wires 1 and 2 as a function of time t.



STOP
END OF EXAM