

PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION I

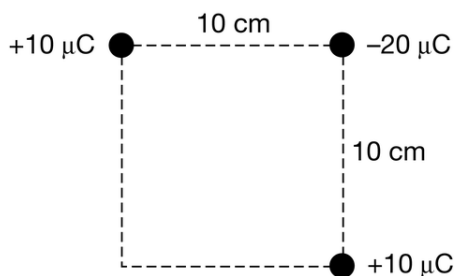
Time—45 minutes

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.

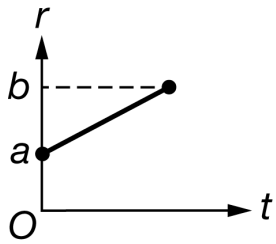
Note: To simplify calculations, you may use $g = 10 \text{ m/s}^2$ in all problems.

Questions 1-2

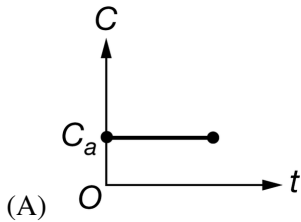
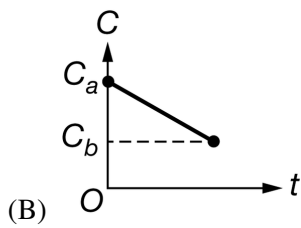
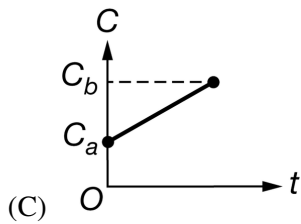
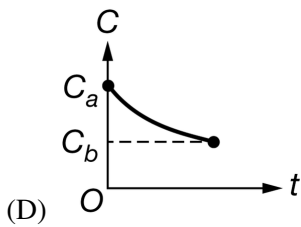
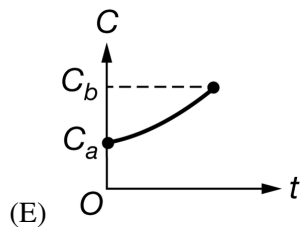
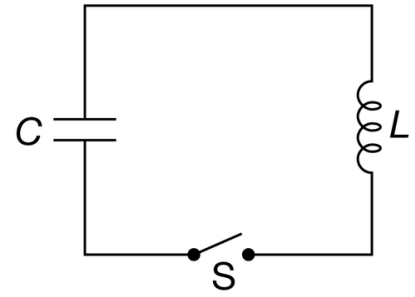


Two particles, each with charge $+10 \mu\text{C}$, are fixed in place at opposite corners of a square, and a particle with charge $-20 \mu\text{C}$ is fixed in place at one of the other corners, as shown in the figure above. The length of each side of the square is 10 cm .

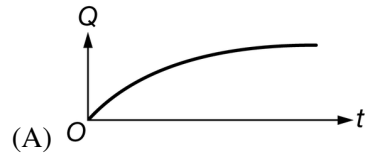
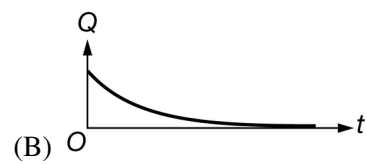
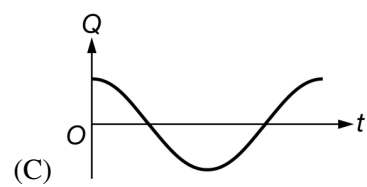
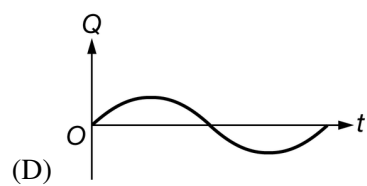
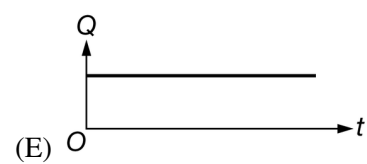
1. A particle with charge $-5 \mu\text{C}$ is placed in the exact center of the square and then released. In what direction, if any, will it initially move?
 - (A) Toward the top of the page.
 - (B) Toward the bottom of the page.
 - (C) Toward the corner of the square with the $-20 \mu\text{C}$ particle.
 - (D) Toward the empty corner of the square.
 - (E) In no direction, because it will not move.
2. The $-5 \mu\text{C}$ particle is now removed and a different particle is placed at the remaining corner of the square. After those changes, the electric potential at the center of the square is zero. What is the charge on the new particle?
 - (A) $-20 \mu\text{C}$
 - (B) $-10 \mu\text{C}$
 - (C) Zero
 - (D) $+10 \mu\text{C}$
 - (E) $+20 \mu\text{C}$



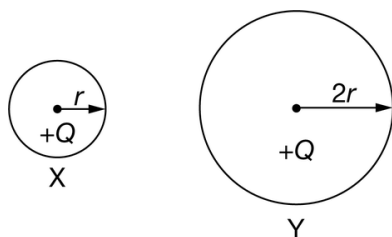
3. An isolated metallic sphere of radius a has a capacitance C_a . Suppose the radius of the sphere could be increased over time to a new radius b , as shown in the figure above. Which of the following would be the graph of the sphere's capacitance C as a function of time t ?



4. In the circuit shown above, the capacitor is initially charged. Which of the following graphs best represents the charge Q on the capacitor versus time t after switch is closed at time $t = 0$?



Questions 5-6



Note: Figure not drawn to scale.

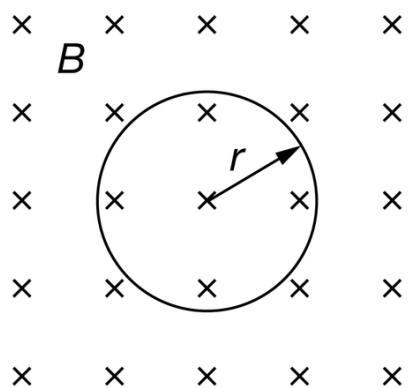
The two conducting spheres shown above each initially have a net positive charge $+Q$. Sphere X has radius r and sphere Y has radius $2r$. The two spheres are held fixed at a separation much greater than their radii. A conducting wire is now used to connect the two spheres. After any resulting current flow has ceased, the wire is removed.

5. The net charge on sphere X after the wire is removed is

- (A) $+\frac{1}{3}Q$
- (B) $+\frac{1}{2}Q$
- (C) $+\frac{2}{3}Q$
- (D) $+Q$
- (E) $+\frac{3}{2}Q$

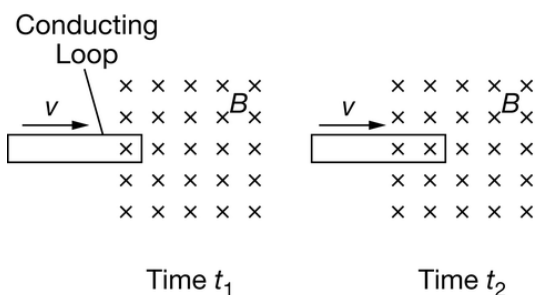
6. What is the ratio V_X/V_Y of the electric potential at the surface of sphere X to the electric potential at the surface of sphere Y after the wire is removed?

- (A) $1/4$
- (B) $1/2$
- (C) $1/1$
- (D) $2/1$
- (E) $4/1$



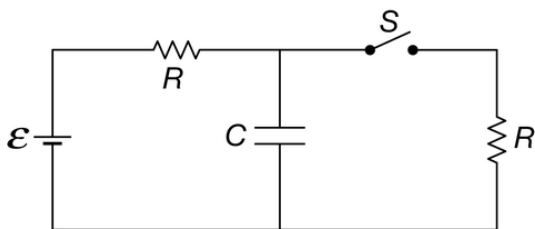
7. A single loop of wire is at rest in a magnetic field that is directed into the page, as shown in the figure above. The loop has a radius of r and a resistance of R . The magnetic field has a magnitude B that changes as a function of time t according to the equation $B = \alpha t + \beta t^2$, where α and β are both positive constants in units of T/s and T/s², respectively. Which of the following expressions gives the current in the loop as a function of time t ?

- (A) $\frac{\beta t \pi r^2}{R}$
- (B) $\frac{(\alpha + 2\beta t) \pi r^2}{R}$
- (C) $\frac{(\alpha + 2\beta t) t \pi r^2}{R}$
- (D) $\frac{(\beta t) 2\pi r}{R}$
- (E) $\frac{(\alpha + 2\beta t) 2\pi r}{R}$



8. A rectangular conducting loop is moving at constant speed v into a uniform magnetic field of magnitude B that is directed into the page. At the two times t_1 and t_2 shown in the figures, the currents in the loop are I_1 and I_2 , respectively. Which of the following correctly compares currents I_1 and I_2 provides evidence?

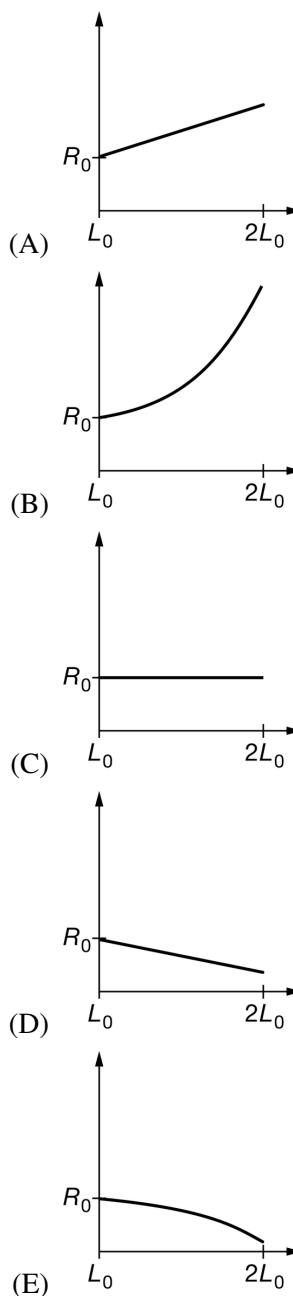
- (A) $I_2 < I_1$, because more of the loop is in the field at time t_2 .
 (B) $I_2 > I_1$, because it takes more force to move the loop at constant speed at time t_2 .
 (C) $I_2 = I_1$, because the current in the loop is zero at both times.
 (D) $I_2 = I_1$, because the loop experiences the same rate of change in flux at both times.
 (E) $I_2 > I_1$, because more of the loop is in the field at time t_2 .



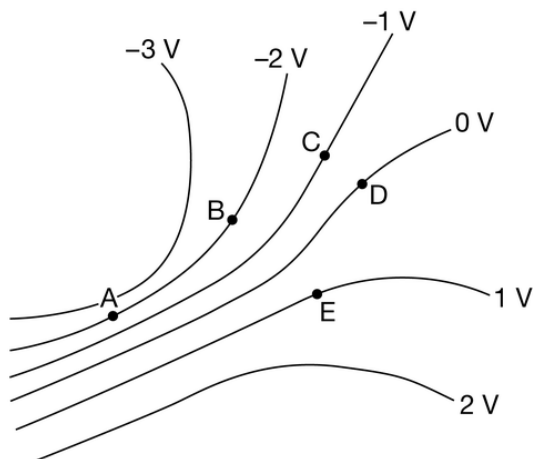
9. In the circuit shown above, switch S is left open for a very long period of time and is then closed. What is the initial current that passes through S immediately after it is closed?

- (A) 0
 (B) $\frac{\varepsilon}{2R}$
 (C) $\frac{\varepsilon}{R}$
 (D) $\frac{2\varepsilon}{R}$
 (E) $\frac{\varepsilon}{RC}$

10. A cylindrical resistor of resistance R_0 and length L_0 is created using a total volume V_0 of a flexible material with constant resistivity. The resistor is carefully stretched so that its volume does not change, it remains a cylinder, and its length doubles. Which of the following graphs best shows the resistance of the wire as a function of the length of the wire as the wire is stretched?

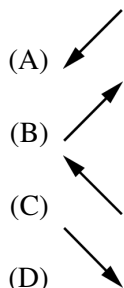


Questions 11-13



The diagram above shows equipotential lines in a particular region.

11. Which of the following vectors, if any, best shows the direction of the electric field at point D?



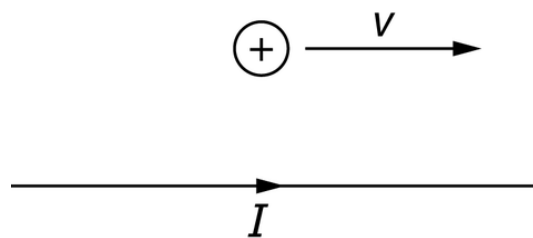
(E) None of the above; the magnitude of the field is zero.

12. At which of the following points is the magnitude of the electric field greatest?

(A) A
(B) B
(C) C
(D) D
(E) E

13. What is the work done by the electric force in moving an electron from point B to point A?

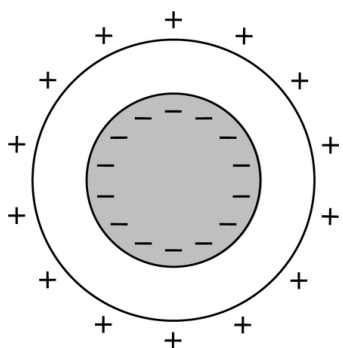
(A) -2.0 J
(B) 0 J
(C) $3.2 \times 10^{-19} \text{ J}$
(D) 2.0 J
(E) It cannot be determined because it depends on the path taken from B to A.



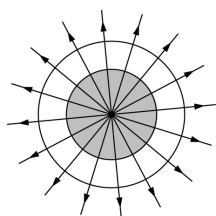
14. A positively charged particle is moving with speed v to the right in the plane of the page, as shown. The wire carries a current I directed toward the right, as shown. Which of the following indicates the direction of the magnetic force on the particle due to the current?



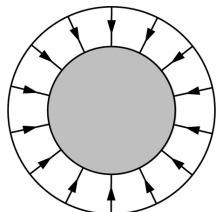
(E) The direction is undefined, because no magnetic force is exerted on the moving particle.



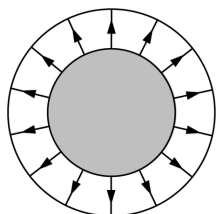
15. A spherical capacitor is constructed with a spherical conductor surrounded by a thin spherical conducting shell. The inner sphere carries a charge $-Q$ and the outer shell carries a charge Q , as shown in the figure above. Which of the following correctly shows the electric field lines for the capacitor?



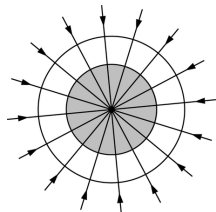
(A)



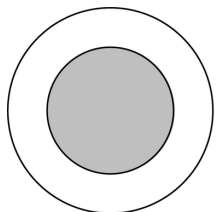
(B)



(C)

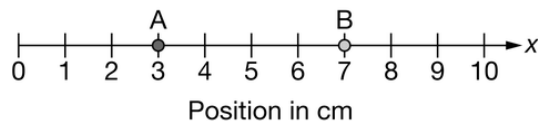


(D)



(E) ($E = 0$ everywhere)

Questions 16-17

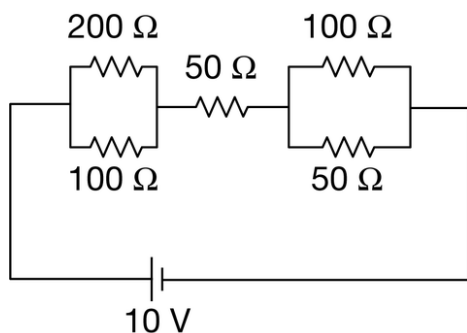


Two small spheres are positioned a distance of 4 cm from each other on the x -axis as shown above. Sphere A has a charge of $+3.0\mu\text{C}$, while sphere B has a charge of $-2.0\mu\text{C}$.

16. The electric potential at $x = 6$ cm is most nearly
- (A) $V = +9.0 \times 10^5$ V
 - (B) $V = +2.1 \times 10^6$ V
 - (C) $V = -9.0 \times 10^5$ V
 - (D) $V = -2.1 \times 10^6$ V
 - (E) $V = -7.0 \times 10^7$ V
17. What is the x -coordinate of the point at which the net electric field due to the spheres is zero?
- (A) 1.8 cm
 - (B) 4.6 cm
 - (C) 5.4 cm
 - (D) 17.8 cm
 - (E) 24.8 cm

18. A steadily increasing current in a resistor of resistance R is given as function of time t by $I(t) = bt$, where b is a constant. What is the total energy dissipated in the resistor during the time interval $0 \leq t \leq T$?

- (A) $2b^2TR$
- (B) $\frac{1}{2}b^2T^2R$
- (C) b^2T^2R
- (D) $\frac{1}{3}b^2T^3R$
- (E) b^2T^3R

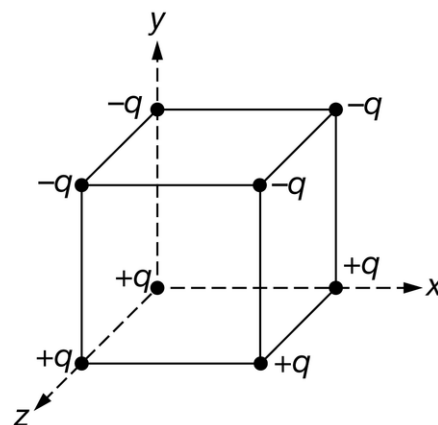


19. The figure above shows five resistors connected to an ideal battery. The equivalent resistance of the circuit is most nearly

- (A) 500 Ω
- (B) 350 Ω
- (C) 200 Ω
- (D) 150 Ω
- (E) 50 Ω

20. A student is constructing a capacitor using two parallel plates and a dielectric. The student intends for the capacitance to be 1.0 F. Once the capacitor is connected to a power supply and the charge is measured, the calculated value of the capacitance is only 0.8 F. Which of the following is a possible reason for the discrepancy?

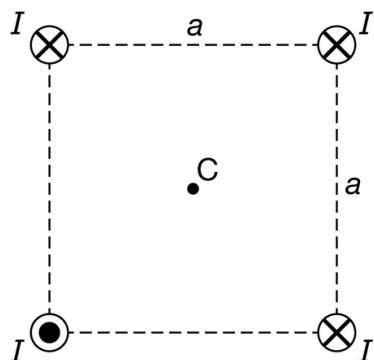
- (A) The potential difference of the power supply is half what was expected.
- (B) The dielectric constant was larger than expected.
- (C) The separation of the plates was greater than what was expected.
- (D) The area of the plates was larger than the student had anticipated.
- (E) The wires used to connect the capacitor had significant resistance.



21. Charges of equal magnitude are placed at the corners of a cube, with charges of $-q$ at the top and charges of $+q$ at the bottom, as shown in the figure above. If a positive charge is placed at the center of the cube, what is the direction of the force on it due to the other charges?

- (A) $+x$
- (B) $+y$
- (C) $-y$
- (D) $+z$
- (E) $-z$

Questions 22-23



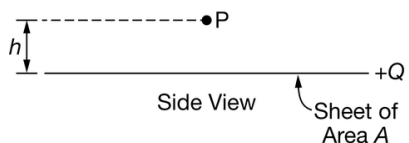
Four very long wires are at the corners of a square and each carry current I perpendicular to the plane and in the directions shown. The sides of the square are length a . Point C is at the center of the square.

22. Which of the following is a correct expression for the magnitude of the net force per length on the top right wire due to the other three wires?

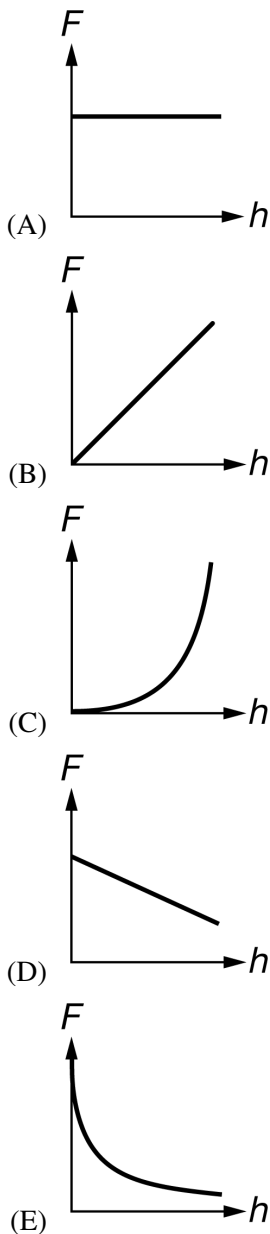
- (A) 0
- (B) $\frac{\sqrt{2}I^2\mu_0}{4\pi a}$
- (C) $\frac{I^2\mu_0}{2\pi a}$
- (D) $\frac{\sqrt{2}I^2\mu_0}{2\pi a}$
- (E) $\frac{\sqrt{2}I^2\mu_0}{4\pi a}$

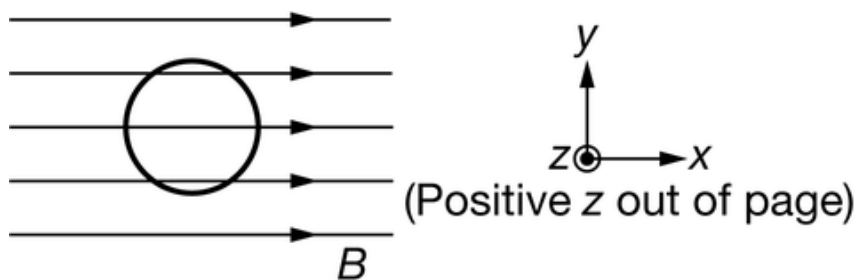
23. If the magnetic field at point C is $2.0 \mu\text{T}$ and $a = 0.10 \text{ m}$, then I is most nearly

- (A) 0.22 A
- (B) 0.35 A
- (C) 0.45 A
- (D) 0.64 A
- (E) 1.3 A



24. A large, horizontal, thin sheet of positive charge of area A has uniform charge density and carries a total charge $+Q$. Point P is a short distance h above the sheet, as shown above. Which of the following is a correct graph for the magnitude of the force F exerted on a proton placed at point P as a function of h ?

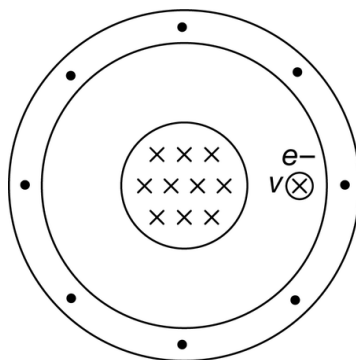




25. A circular loop of wire in the plane of the page is in a uniform magnetic field of magnitude B directed to the right, as shown in the figure above. The magnetic field extends above and below the page. For which of the following would there be an induced current in the loop?

- I. Rotate the loop around the x -axis.
- II. Rotate the loop around the y -axis.
- III. Rotate the loop around the z -axis.

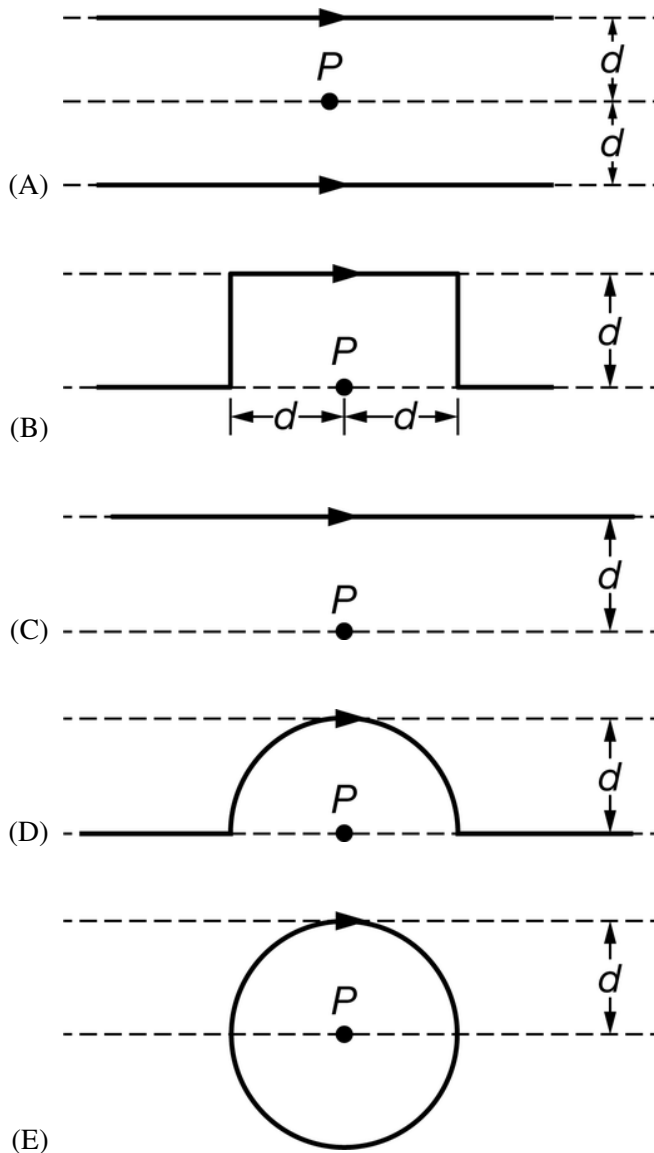
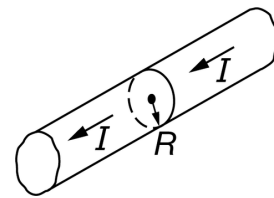
- (A) I only
- (B) II only
- (C) III only
- (D) I and II only
- (E) I, II, and III



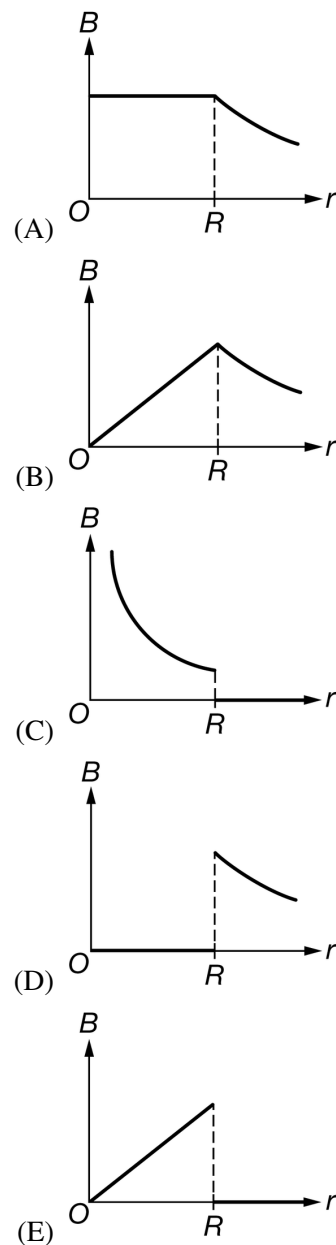
26. A coaxial cable consists of a cylindrical wire inside of a cylindrical shell of wire. The inner wire has a current I directed into the page, and the outer wire has a current I out of the page. An electron has a velocity directed into the page, as shown in the figure above. What is the direction of the magnetic force exerted on the electron?

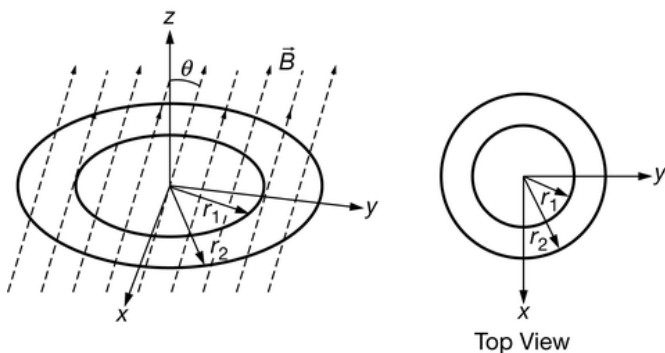
- (A) Toward the left side of the page.
- (B) Toward the right side of the page.
- (C) Toward the bottom of the page.
- (D) There is no magnetic force on the electron because the magnetic field in the region between the inner and outer wires is parallel to the velocity.
- (E) There is no magnetic force on the electron because there is no magnetic field in the region between the inner and the outer wires.

27. Wires are shown in five different configurations below. Option A shows two wires, and all other options show a single wire. For all the configurations, the wires have a current I . For each configuration, a labeled point P is the same distance d from the indicated wires. Which of the following configurations creates a magnetic field of the greatest magnitude at point P ?



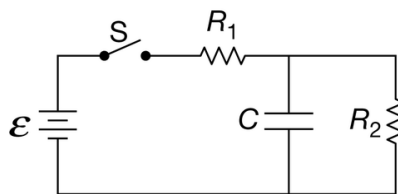
28. The long wire of radius R shown above carries a current I that is uniformly distributed over its cross-sectional area. Which of the following graphs best represents the magnitude of the magnetic field B as a function of distance r from the axis of the wire?





29. Two circular loops of thin metal wire of radius r_1 and radius r_2 are positioned on the horizontal xy -plane. A magnetic field of magnitude B is directed upward through the loops at an angle θ with the vertical z -axis, as shown in the figure above. The magnetic flux in the space between the loops is

- (A) $2\pi B \sin \theta (r_2 - r_1)$
- (B) $2\pi B \cos \theta (r_2 - r_1)$
- (C) $\pi B \cos \theta (r_2 - r_1)^2$
- (D) $\pi B \sin \theta (r_2^2 - r_1^2)$
- (E) $\pi B \cos \theta (r_2^2 - r_1^2)$



30. A circuit contains an ideal battery with potential difference ϵ , two resistors with resistances R_1 and R_2 , a capacitor of capacitance C , and switch S , as shown above. The switch is closed. A long time after the switch is closed, the positive plate of the capacitor has charge $+Q$. What change to the circuit can a student make to increase the amount of charge stored on the positive plate of the capacitor?

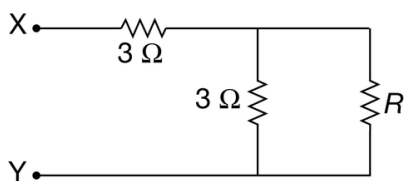
- (A) Replace R_1 with a new resistor of larger resistance.
- (B) Replace R_2 with a new resistor of larger resistance.
- (C) Replace the capacitor with a capacitor that is identical except that there is more separation between its plates.
- (D) Replace the capacitor with a capacitor that is identical except that the plates have a smaller area.
- (E) Replace the battery with an ideal battery that has a lower potential difference.

31. Isolated conducting spheres 1 and 2 have radii R_1 and R_2 , respectively. The spheres are separated by a large distance, and spheres 1 and 2 have charges of $+Q_1$ and $+Q_2$, respectively. The electric field at the surface of sphere 1 is E_1 , and the electric field at the surface of sphere 2 is E_2 . The ratio E_1/E_2 is

- (A) $\frac{Q_1 R_2}{Q_2 R_1}$
- (B) $\frac{Q_1 R_1}{Q_2 R_2}$
- (C) $\frac{Q_1 R_2^2}{Q_2 R_1^2}$
- (D) $\frac{Q_1 R_1^2}{Q_2 R_2^2}$
- (E) $\frac{Q_2 R_1^2}{Q_1 R_2^2}$

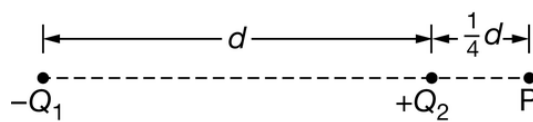
32. An electric heater and a lamp are connected in parallel across a 120 V circuit. The heater operates at 1000 W and the lamp operates at 100 W. The ratio of the resistance of the heater to the resistance of the lamp is

- (A) $\frac{1}{100}$
 (B) $\frac{1}{10}$
 (C) 1
 (D) 10
 (E) 100



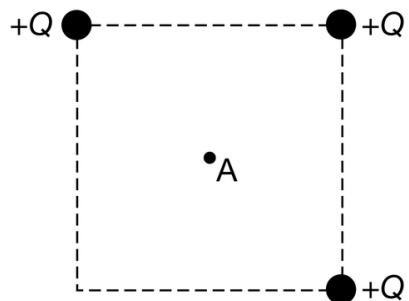
33. The diagram above shows a segment of a circuit for which the equivalent resistance between points X and Y is 5 Ω . What is the value of resistor R?

- (A) 1 Ω
 (B) 2 Ω
 (C) 3 Ω
 (D) 5 Ω
 (E) 6 Ω



34. Two stationary point charges $-Q_1$ and $+Q_2$ are separated by a distance d as shown above. If the distance from $+Q_2$ to point is $\frac{1}{4}d$, what must be the relationship between the magnitudes of the charges for the electric field to be zero at point P?

- (A) $Q_1 = 4Q_2$
 (B) $Q_1 = 5Q_2$
 (C) $Q_1 = 9Q_2$
 (D) $Q_1 = 16Q_2$
 (E) $Q_1 = 25Q_2$



35. Three particles of equal charge $+Q$ are arranged at 3 corners of a square, as shown above. Point A is located at the center of the square. What charge could be placed at the empty corner to make the electric potential at point A zero?

- (A) $+3Q$
 (B) $+Q$
 (C) Zero
 (D) $-Q$
 (E) $-3Q$

STOP
END OF ELECTRICITY AND MAGNETISM SECTION I

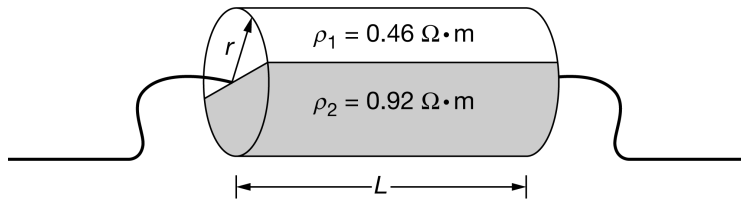
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

Time—45 minutes

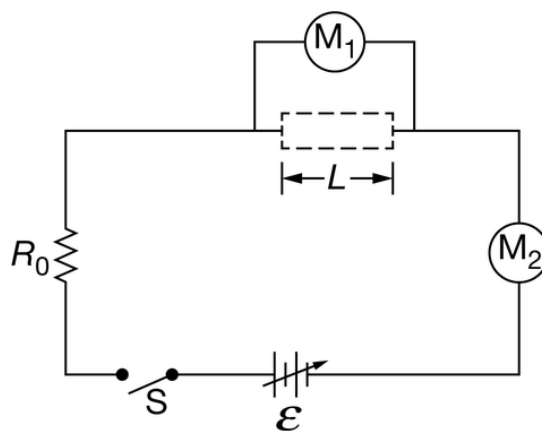
3 Questions

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. A cylinder of length $L = 0.25 \, \text{m}$ and radius $r = 0.020 \, \text{m}$ is made of two different materials, as shown. The top half has a resistivity of $\rho_1 = 0.46 \, \Omega \cdot \text{m}$, and the bottom half has a resistivity of $\rho_2 = 0.92 \, \Omega \cdot \text{m}$. The cylinder has connection wires at the center of each end, as shown.

(a) Calculate the resistance of this cylinder.



- (b) The cylinder from part (a) is placed into the circuit shown above in which the dashed rectangular area represents the cylinder. The rest of the circuit consists of a variable voltage source with potential difference $\mathcal{E}$, ideal meters M_1 and M_2 , switch S , and a resistor of known resistance R_0 . The switch is closed, and a current I is measured for the circuit.

i. Which of the following indicates the measurement made by meter M_1 ? Check all that apply.

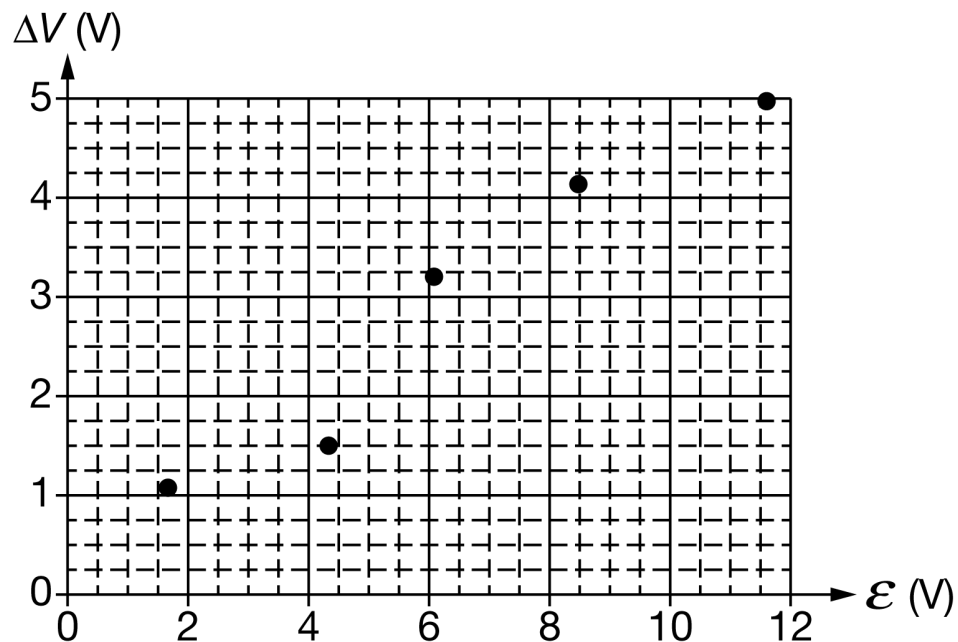
- ☐ Potential difference across the cylinder ☐ Current through the cylinder
☐ Potential difference across resistor R_0 ☐ Current through resistor R_0
☐ Potential difference of the voltage source ☐ Current through the voltage source

ii. Which of the following indicates the measurement made by meter M_2 ? Check all that apply.

- ☐ Potential difference across the cylinder ☐ Current through the cylinder
☐ Potential difference across resistor ☐ Current through resistor
☐ Potential difference of the voltage source ☐ Current through the voltage source

- (c) Derive an expression for the potential difference ΔV across the cylinder once the switch is closed. Express your answer in terms of $\mathcal{E}$, R_0 , the cylinder's resistance R_C , and physical constants, as appropriate.

- (d) Students run an experiment with the circuit in which they measure the potential difference ΔV across the cylinder for several different potential differences of the variable voltage source. The data are plotted on the graph below.



i. Draw a best-fit line to represent the data.

ii. Use your best-fit line to calculate the resistance R_0 .

- (e) i. Identify one possible source of error in the experiment and explain how it would affect the measurement of the potential difference ΔV across the cylinder.

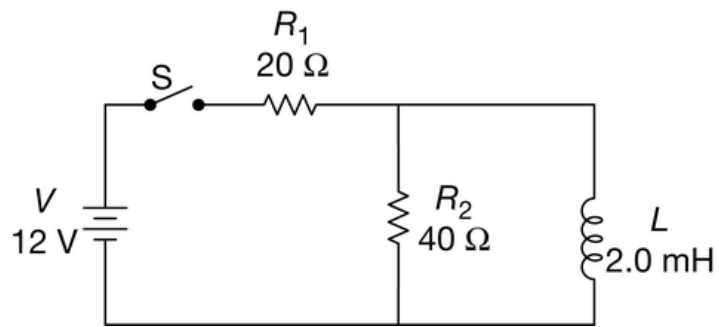
- ii. While conducting the experiment, students notice that the measurement reading on meter M_2 depends on whether meter M_1 is in the circuit. Which of the following relationships is correct about the measurement reading on M_2 ?

_____ It is greater with meter M_1 in the circuit.

_____ It is less with meter M_1 in the circuit.

Explain why the reading on meter M_2 changes when meter M_1 is connected to the circuit.

- iii. Explain how you would change the procedure to determine an experimental value for the resistance of meter M_2 .



2. The circuit shown above consists of an ideal battery, two resistors, an inductor, and a switch. The switch is initially open. At time $t = 0$, the switch is closed.

(a) i. Calculate the current in resistor R_1 immediately after the switch is closed.

ii. Calculate the potential difference across the inductor immediately after the switch is closed.

iii. On the axes below, sketch the potential difference ΔV across the inductor as a function of time t .



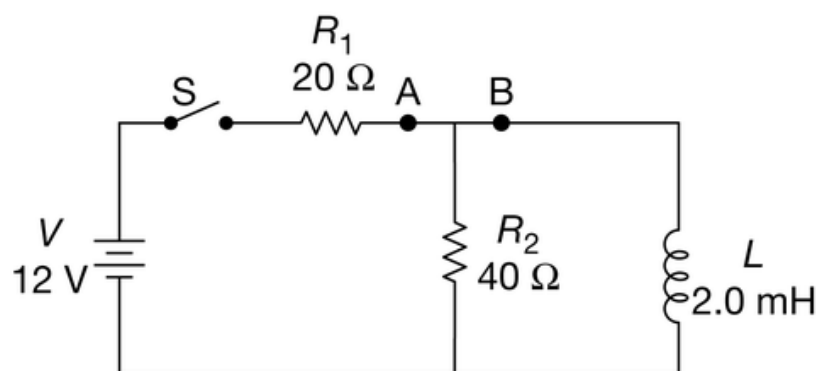
(b) After a long time, the switch is now opened.

i. Calculate the current in resistor immediately after the switch is opened.

ii. Is the current up through R_2 , down through R_2 , or zero?

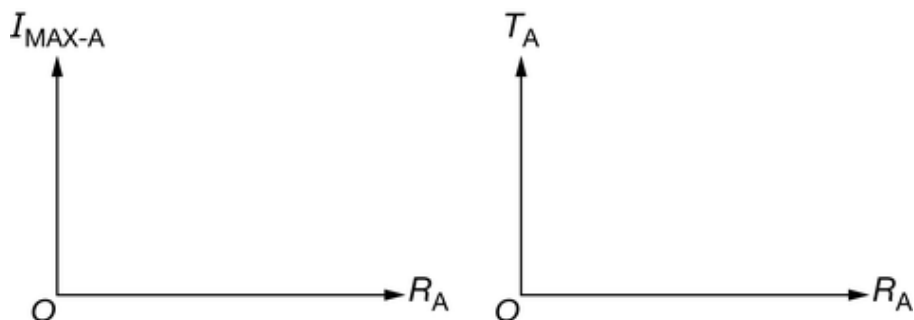
(c) Write, but do NOT solve, the differential equation for the current $I(t)$ as a function of t through the inductor after the switch is opened.

(d) Using integral calculus, derive an equation to show that the equation of the current as a function of time is $I(t) = I_0 e^{-t/\tau}$, where $\tau = \frac{L}{R_2}$.

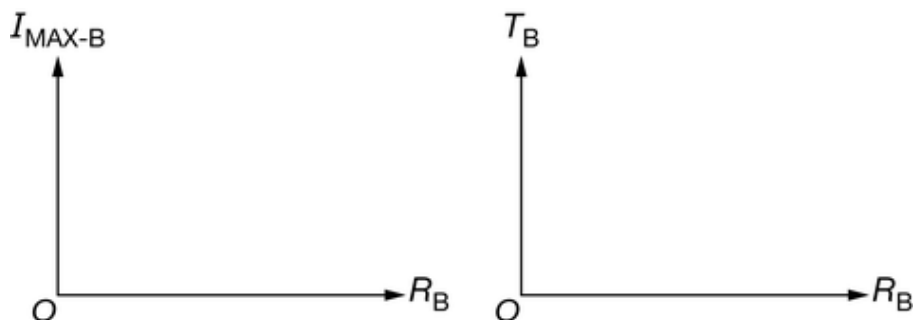


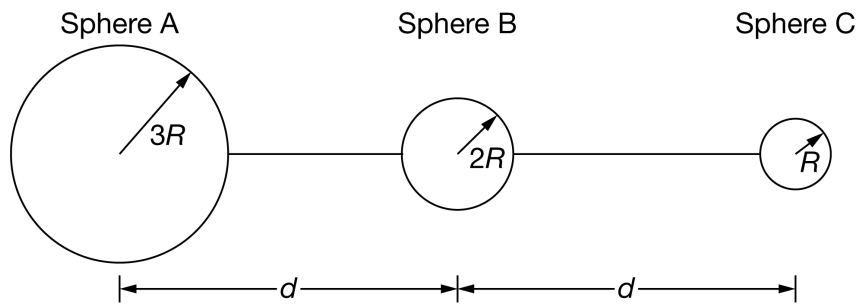
(e) The procedure is repeated, with the switch closed for a long time and then opened. Points A and B are indicated in the circuit diagram, as shown.

- i. Resistors of different resistances R_A are placed at position A . The switch is closed for a long time and then opened. The following two measurements are made for each resistor: the maximum current $I_{\text{MAX-A}}$ in the inductor immediately after the switch is opened and the time T_A it takes the current in the inductor to reach 67% of its initial value after the switch is opened. On the axes below, sketch graphs of $I_{\text{MAX-A}}$ and T_A as functions of R_A .



- ii. Resistors of different resistances R_B are now placed at position B . The switch is closed for a long time and then opened. The following two measurements are made for each resistor: the maximum current $I_{\text{MAX-B}}$ in the inductor immediately after the switch is opened and the time T_B it takes the current in the inductor to reach 67% of its initial value after the switch is opened. On the axes below, sketch graphs of $I_{\text{MAX-B}}$ and T_B as functions of R_B .





Note: Figures not drawn to scale.

3. Three solid conducting spheres are connected with two very long, thin conducting wires, as shown. They are all initially neutral; then a charge of $12Q$ is transferred to the leftmost sphere. Enough time elapses that the spheres achieve electrostatic equilibrium. Assume $d \gg R$ and that the system of spheres and wires is isolated from any external forces.

(a) Calculate the charge on each sphere. Express your answers in terms of Q .

(b) Rank the spheres according to their surface charge density, with 1 indicating the greatest surface charge density. If two spheres have the same value, then give them the same ranking.

_____ Sphere A _____ Sphere B _____ Sphere C

(c) The magnitudes of the electric field at the surfaces of spheres A and C are E_A and E_C , respectively. Calculate the ratio E_A/E_C .

- (d) Is the tension in the left wire greater than, less than, or equal to the tension in the right wire? Assume nonelectric forces are negligible.

_____ Greater than _____ Less than _____ Equal to

Justify your answer.

The wire between spheres B and C breaks. Assume the force of gravity is negligible.

- (e) Determine the new charges on spheres A and B . Express your answer in terms of Q .

Justify your answer.

- (f) After the wire breaks, sphere C accelerates away from the other two spheres.

- i. On the dot below that represents sphere C , draw an arrow that represents the direction of the acceleration of sphere C immediately after the wire breaks. The arrow must start on, and point away from, the dot.



- ii. Derive an expression for the kinetic energy of the system of three spheres when sphere C is very far away from spheres A and B . Express your answer in terms of q , R , d , and physical constants, as appropriate.

STOP
END OF EXAM

AP Physics C Electricity and Magnetism

2021

APPENDIX - ANSWERS

Matching multiple-choice answers and free-response scoring follow.

3 Answers for Multiple Choice Questions

Question	Answer	Question	Answer	Question	Answer	Question	Answer	Question	Answer
1	D	8	D	15	B	22	B	29	E
2	C	9	C	16	C	23	B	30	B
3	C	10	B	17	E	24	A	31	C
4	C	11	C	18	D	25	B	32	B
5	C	12	A	19	D	26	B	33	E
6	C	13	B	20	C	27	E	34	E
7	B	14	B	21	B	28	B	35	E

4 Scoring Guidelines

4.1 Question 1

Part (a): 3 points

1 point is earned for using a correct equation to calculate resistance for each half of the wire.

1 point is earned for using the correct area in the equation for resistance.

$$R_1 = \frac{\rho_1 L}{A} = 183\Omega$$

$$R_2 = \frac{\rho_2 L}{A} = 366\Omega$$

1 point is earned for using the equation for parallel resistors to calculate the equivalent resistance

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \Rightarrow R = 122\Omega$$

Part (b): 2 points

1 point is earned for selecting "Potential difference across the cylinder".

1 point is earned for selecting "Current through the cylinder", "Current through resistor", and "Current through the voltage source".

Part (c): 2 points

1 point is earned for using the correct equivalent resistance to determine the current.

$$I = \frac{\Delta V}{R} = \frac{\Delta V}{R_{eq}} = \frac{\varepsilon}{R_0 + R_C}$$

1 point is earned for correctly substituting into Ohm's law to derive the potential difference across the resistor.

$$\Delta V = IR = \left(\frac{\varepsilon}{R_0 + R_C} \right) R_C = \frac{\varepsilon R_C}{R_0 + R_C}$$

Part (d): 4 points

1 point is earned for drawing an appropriate best fit line.

1 point is earned for calculating slope using two points from the best fit line

$$\text{Slope} = \frac{\Delta y}{\Delta x} = 0.41$$

1 point is earned for relating the slope to R_0 .

$$\text{Slope} = \frac{R_C}{R_0 + R_C} \Rightarrow R_0 + R_C = \frac{R_C}{\text{Slope}} \Rightarrow R_0 = \frac{R_C}{\text{Slope}} - R_C$$

1 point is earned for correctly substituting into the equation.

$$R_0 = \frac{122\Omega}{0.41} - 122\Omega = 176\Omega$$

Part (e): 4 points

1 point is earned for identifying a possible source of error and explaining how it would affect the measurement ΔV .

Example Response: The resistance of the wires, meter M_2 , and the battery will cause the measurement of ΔV to be lower than it should be.

1 point is earned for selecting “greater” and attempting a relevant explanation.

1 point is earned for a correct explanation.

Example Response: Because meter M_1 is placed in parallel with the cylinder, the equivalent resistance of the circuit decreases; thus, the current in the circuit which is the reading on meter M_2 will increase.

1 point is earned for correctly explaining how to determine the resistance of meter M_2 .

Example Response: Move meter M_1 so that it is in parallel with and can measure the potential across meter M_2 . Then, use the measurement of the two meters and Ohm’s law to determine the resistance of meter M_2 .

4.2 Question 2

Part (a): 5 points

1 point is earned for using Ohm's law to calculate the current in R_1 .

1 point is earned for a correct numerical answer with units.

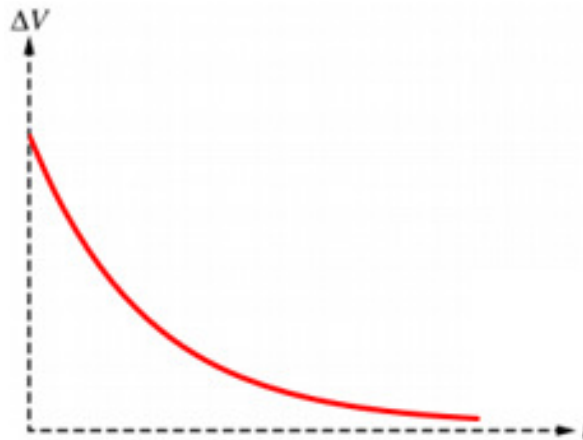
$$I = \frac{\Delta V}{R} = \frac{\Delta V}{R_1 + R_2} = 0.20 \text{ A}$$

1 point is earned for using a correct equation to calculate the potential difference across the inductor immediately after the switch is closed.

$$V_L = V_{R2} = IR_2$$

1 point is earned for correctly substituting into the correct equation.

1 point is earned for a concave up curve with an asymptote at the horizontal axis.



Part (b): 2 points

1 point is earned for an indication that the current through the inductor after the switch is open is equal to the current through R_1 before the switch was open.

$$I = \frac{\Delta V}{R_1} = 0.60 \text{ A}$$

1 point is earned for selecting "Up".

Part (c): 1 points

1 point is earned for using Kirchhoff's loop rule to write an appropriate differential equation.

$$V_L - V_{R2} = 0 \Rightarrow -L \frac{dI}{dt} - IR_2 = 0$$

Part (d): 2 points

1 point is earned for separating the variables.

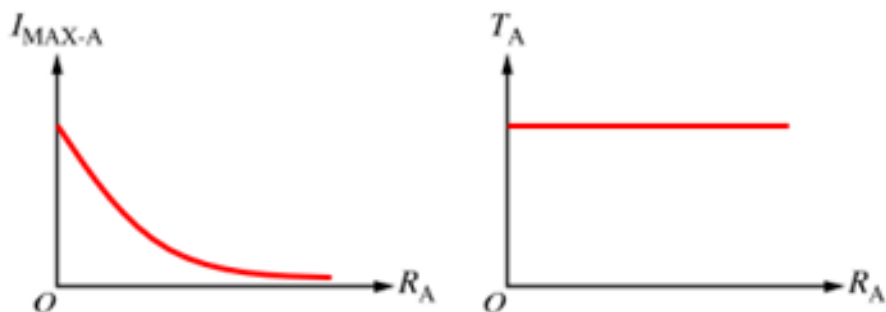
$$-L \frac{dI}{dt} = IR_2 \Rightarrow \frac{1}{I} dI = -\frac{R_2}{L} dt$$

1 point is earned for integrating with correct limits or constant of integration.

$$\int_{I_0}^{I(t)} \frac{1}{I} dI = \frac{t}{0} - \frac{R_2}{L} dt' \Rightarrow [\ln I]_{I_0}^{I(t)} = -\frac{R_2}{L} [t']_0^t \Rightarrow \ln\left(\frac{I(t)}{I_0}\right) = -\frac{R_2 t}{L} \Rightarrow I(t) = I_0 e^{-\frac{t R_2}{L}} = I_0 e^{-\frac{t}{\tau}}$$

Part (e): 5 points

1 point is earned for a graph that is concave up and indicates that the maximum current decreases as increases.

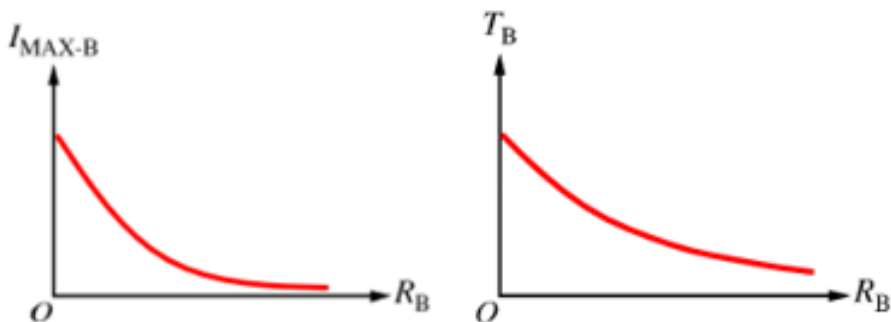


1 point is earned for a horizontal line that is above the horizontal axis.

1 point is earned for a graph that is concave up and indicates that the maximum current decreases as R_B increases.

1 point is earned for a graph that is concave up and indicates that the time T_B decreases as R_B increases.

1 point is earned for consistency of the maximum current graphs in parts (e)(i) and (e)(ii).



4.3 Question 3

Part (a): 3 points

1 point is earned for indicating that the total charge on the three spheres is $12Q$.

$Q_{\text{tot}} = Q_A + Q_B + Q_C = 12Q$ 1 point is earned for using the electric potential of the sphere to derive a relationship between the charges on each sphere.

$$V_A = V_B \Rightarrow \frac{kQ_A}{r_A} = \frac{kQ_B}{r_B} \Rightarrow \frac{Q_A}{3R} \frac{Q_B}{2R} \Rightarrow Q_B = \frac{2}{3}Q_A$$

$$V_A = V_C \Rightarrow \frac{kQ_A}{r_A} = \frac{kQ_C}{r_C} \Rightarrow \frac{Q_A}{3R} \frac{Q_C}{R} \Rightarrow Q_C = \frac{1}{3}Q_A$$

1 point is earned for the correct calculation of the charge on each sphere.

$$Q_A + \frac{2}{3}Q_A + \frac{1}{3}Q_A = 12Q \Rightarrow Q_A = 6Q$$

$$Q_B = \frac{2}{3}Q_A = 4Q$$

$$Q_C = \frac{1}{3}Q_A = 2Q$$

Part (b): 1 points

1 point is earned for correctly ranking the surface charge density of the spheres.

Example Answer: 3 Sphere A 2 Sphere B 1 Sphere C

Part (c): 2 points

1 point is earned for using an appropriate equation for electric field in calculating the ratio.

1 point is earned for correctly substituting expressions for charges and distances into the equation for the ratio.

$$\frac{Q_A}{Q_C} = \frac{\frac{1}{4\pi\epsilon_0} \frac{Q_A}{R_A^2}}{\frac{1}{4\pi\epsilon_0} \frac{Q_B}{R_B^2}} = \frac{Q_A R_C^2}{Q_C R_A^2} = \frac{(6Q)R^2}{(2Q)(3R)^2} = \frac{1}{3}$$

Part (d): 2 points

1 point is earned for selecting “Greater than” and attempting a relevant justification.

1 point is earned for a correct justification.

Example Response: According to Coulomb’s law, spheres A and B will have a greater force of repulsion than spheres B and C; therefore, the wire on the left has a greater tension.

Part (e): 3 points

1 point is earned for indicating that the total charge on spheres A and B stays the same or consistent with respective charges indicated in part (a).

1 point is earned for a justification indicating that the total charge on spheres A and B is the same.

1 point is earned for a justification indicating that the electric potential of spheres A and B is the same.

Example Response: The total charge on spheres A and B is the same before and after the wire is cut. The electric potential of both spheres must also still be the same. Since these two relationships are unchanged, the charge on each sphere is the same.

Part (f): 4 points

1 point is earned for a single arrow pointing to the right.



1 point is earned for setting the change in kinetic energy equal to the change in electric potential energy of the three-sphere system.

$$\Delta K = \Delta U$$

1 point is earned for using the correct change in electric potential energy between the spheres.

$K = U_{AB} + U_{AC} + U_{BC} - U_{AB} = U_{AC} + U_{BC}$ 1 point is earned for correctly substituting into the above equation consistent with part (a).

$$K = \frac{kQ_A Q_C}{r_{AC}} + \frac{kQ_B Q_C}{r_{BC}} = k \left(\frac{(6Q)(2Q)}{2d} + \frac{(4Q)(2Q)}{d} \right) = \frac{kQ^2}{d} (6 + 8) = \frac{14kQ^2}{d}$$