

Begin your response to **QUESTION 1** on this page.

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.

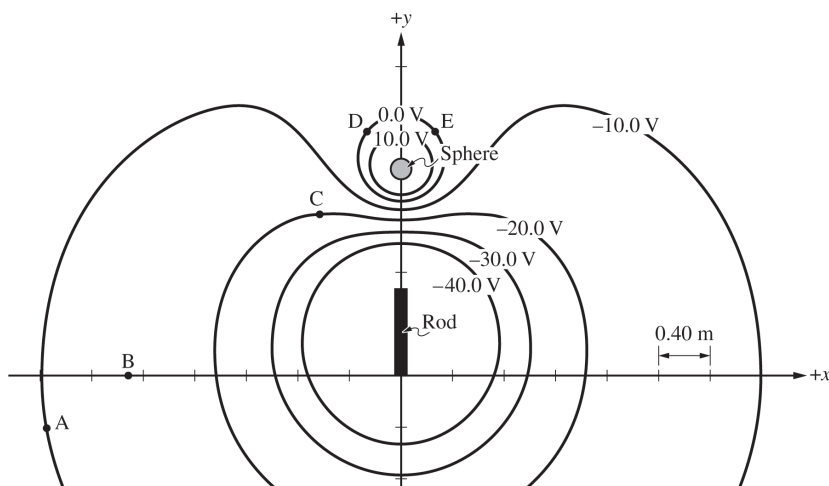


Figure 1

1. A nonconducting rod of uniform negative linear charge density is near a sphere with charge $+1.0 \text{ nC}$. The rod and sphere are held at rest on the y -axis, as shown in Figure 1. Equipotential lines and positions A, B, C, D, and E are labeled. Adjacent tick marks on the x -axis and on the y -axis are 0.40 m apart.

- (a) **Calculate** the absolute value of the electric flux through the Gaussian surface whose cross section is the 0.0 V equipotential line.

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A positive test charge (not shown) is placed and held at rest at Position C. An external force is applied to the test charge to move the test charge to different positions in the order of $C \rightarrow E \rightarrow D \rightarrow A$. The test charge is held momentarily at rest at each position.

- (b) The bar shown in Figure 2 represents the absolute value of the work W_{CE} done by the external force on the test charge to move the test charge from Position C to Position E.

- i. Complete the following tasks on Figure 2.

- **Draw** a bar to represent the relative absolute value of the work W_{ED} done by the external force on the test charge to move the test charge from Position E to Position D.
- **Draw** a bar to represent the relative absolute value of the work W_{DA} done by the external force on the test charge to move the test charge from Position D to Position A.
- The height of each bar should be proportional to the value of W_{CE} . If $W_{ED} = 0$ and/or $W_{DA} = 0$, write a "0" in the corresponding columns, as appropriate.

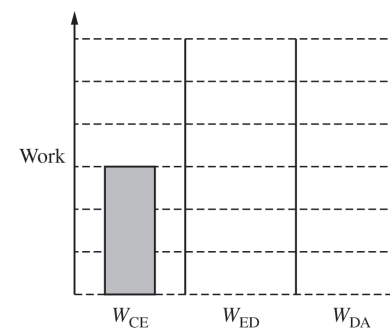


Figure 2

- ii. **Calculate** the approximate magnitude of the x -component of the electric field at Position B.

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The positive test charge is placed at Position C. The test charge is then released from rest.

(c) **Indicate** the direction (not components) of the net electric force exerted on the test charge immediately after the test charge is released from rest.

_____ $+x$ _____ $+y$ _____ Directly away from the sphere

_____ $-x$ _____ $-y$ _____ Directly toward the sphere

Without using equations, **justify** your answer using physics principles.

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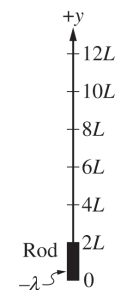
Continue your response to **QUESTION 1** on this page.

Figure 3

The sphere and the test charge are removed. The rod has length $2L$ and uniform negative linear charge density $-\lambda$. The rod is held at rest on the y -axis in the orientation shown in Figure 3. Position P (not shown) is located on the y -axis a distance y_P from the origin, where $y_P > 2L$.

(d) The electric potential V_P at y_P is $V_P = -k\lambda \ln\left(\frac{y_P}{y_P - 2L}\right)$.

i. Using integral calculus, **derive** the expression for V_P provided.

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- ii. On Figure 4, **sketch** a graph of the y -component E_y of the electric field resulting from the rod as a function of y in the region $2L < y < 12L$.

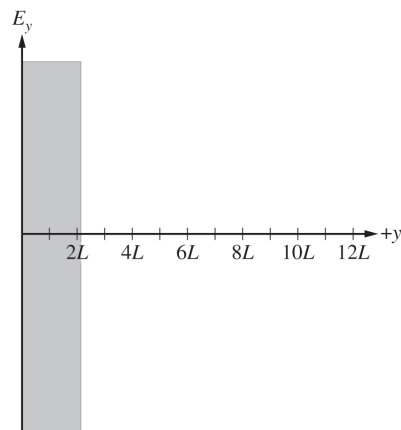
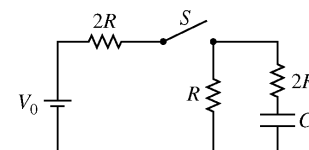


Figure 4

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1. The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0 , a capacitor of capacitance C , and a switch S . The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0 , R , C , and fundamental constants, as appropriate.

- (a) Derive an expression for the steady-state current supplied by the battery.
- (b) Derive an expression for the charge on the capacitor.
- (c) Derive an expression for the energy stored in the capacitor.

Now the switch is opened at time $t = 0$.

- (d) Write, but do NOT solve, a differential equation that could be used to solve for the charge $q(t)$ on the capacitor as a function of the time t after the switch is opened.

(e)

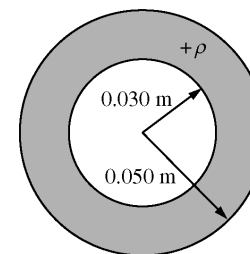
- i. Calculate the current in resistor R immediately after the switch is opened.
- ii. On the axes below, sketch the current in the circuit as a function of time from time $t = 0$ to a long time after the switch is opened. Explicitly label the maxima with numerical values or algebraic expressions, as appropriate.



- (f) Is the total amount of energy dissipated in the resistors after the switch is opened greater than, less than, or equal to the amount of energy stored in the capacitor calculated in part (c) ?

____ Greater than ____ Less than ____ Equal to

Justify your answer.



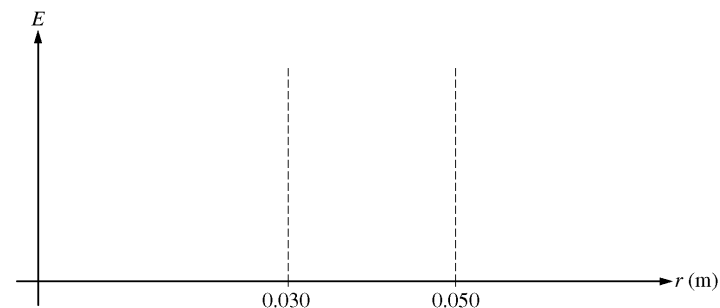
2. A nonconducting hollow sphere of inner radius 0.030 m and outer radius 0.050 m carries a positive volume charge density ρ , as shown in the figure above. The charge density ρ of the sphere is given as a function of the distance r from the center of the sphere, in meters, by the following.

$$r < 0.030 \text{ m: } \rho = 0$$

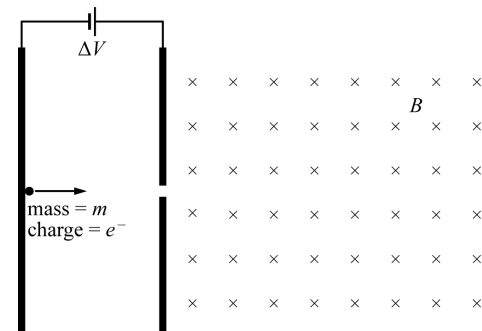
$$0.030 \text{ m} < r < 0.050 \text{ m: } \rho = b/r, \text{ where } b = 1.6 \times 10^{-6} \text{ C/m}^2$$

$$r > 0.050 \text{ m: } \rho = 0$$

- (a) Calculate the total charge of the sphere.
- (b) Using Gauss's law, calculate the magnitude of the electric field E at the outer surface of the sphere.
- (c) On the axes below, sketch the magnitude of the electric field E as a function of distance r from the center of the sphere.



- (d) Calculate the electric potential V at the outer surface of the sphere. Assume the electric potential to be zero at infinity.
- (e) A proton is released from rest at the outer surface of the sphere at time $t = 0$ s.
- Calculate the magnitude of the initial acceleration of the proton.
 - Calculate the speed of the proton after a long time.



3. Two plates are set up with a potential difference V between them. A small sphere of mass m and charge $-e$ is placed at the left-hand plate, which has a negative charge, and is allowed to accelerate across the space between the plates and pass through a small opening. After passing through the small opening, the sphere enters a region in which there is a uniform magnetic field of magnitude B directed into the page, as shown above. Ignore gravitational effects. Express all algebraic answers in terms of V , m , e , B , and fundamental constants, as appropriate.
- (a)
- What is the initial direction of the force on the sphere as it enters the magnetic field?
 ____ Into the page ____ Out of the page
 ____ Toward the top of the page ____ Toward the bottom of the page
 - Describe the path taken by the sphere after it enters the magnetic field.
- (b) Derive an expression for the speed of the sphere as it passes through the small opening.
- (c) Derive an expression for the radius of the path taken by the sphere as it moves through the magnetic field.

An experiment is performed in which a beam of electrons is accelerated across the space between the plates and passes through the small opening. After passing through the opening, the electrons travel in a semicircular path and strike the right-hand plate. The potential difference between the plates is varied in regular increments, as shown in the table below. For each potential difference, the magnetic field is varied in order to cause the beam to strike the right-hand plate at a distance of 0.020 m from the opening.

Potential difference (V)	60	70	100	110	120	140
Magnetic field ($T \times 10^{-3}$)	2.62	2.78	3.39	3.54	3.78	3.99

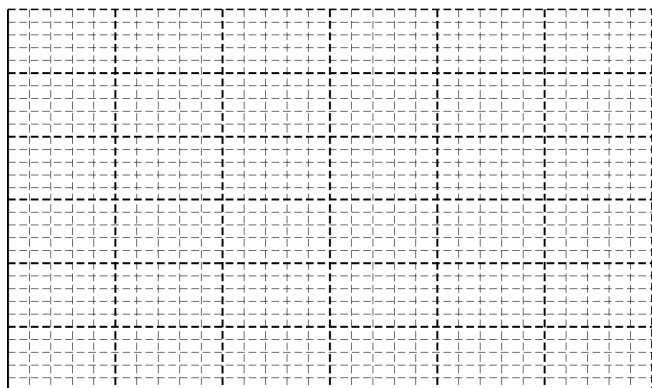
- (d) Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for the mass-to-charge ratio of an electron.

Vertical axis: _____

Horizontal axis: _____

Use the remaining columns in the table above, as needed, to record any quantities that you indicated that are not given. Label each column you use and include units.

- (e) On the graph below, plot the relationship determined in part (d). Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



- (f) Using the straight line from part (e), determine the mass-to-charge ratio of an electron.

STOP
END OF EXAM

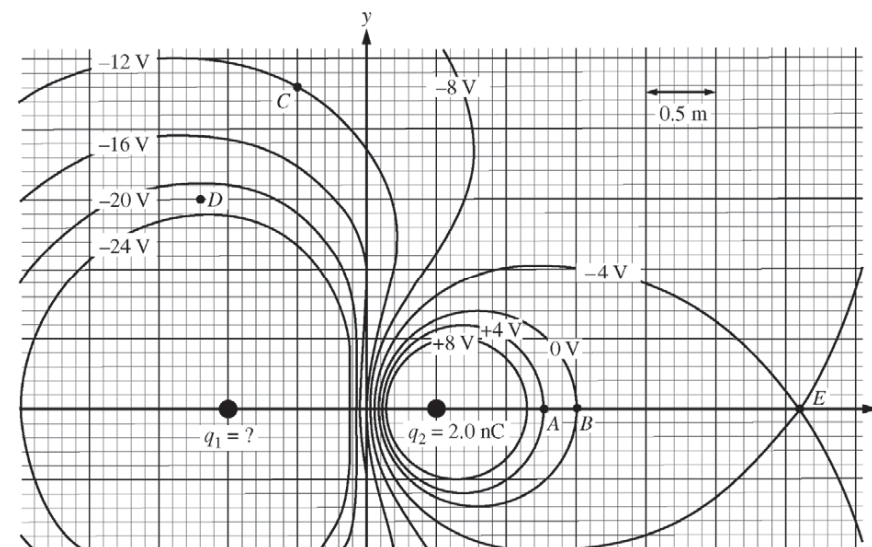
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E&M.1.

Two point charges, q_1 and q_2 , are fixed in place on the x -axis at positions $x_1 = -1.00$ m and $x_2 = +0.50$ m, respectively. Charge q_2 has a value of $+2.0$ nC. Values of electric potential are illustrated by the given equipotentials in the diagram shown above, which is drawn to scale.

- Calculate the value of q_1 .
- At point C on the diagram, draw a vector representing the direction of the electric field at that point.
- Calculate the approximate magnitude of the electric field strength at point D on the diagram.
- The equipotential labeled 0 V is the cross section of a nearly spherical surface. Calculate the electric flux for this surface.

- (e) A proton is placed at point A and then released from rest.
- Calculate the work done by the electric field on the proton as it moves from point A to point E.
 - Calculate the speed of the proton when it reaches point E.
- (f) An electron is released from rest at point B. Which of the following indicates the direction of the initial acceleration, if any, of the electron?
- ☐ Up ☐ Down
- ☐ Left ☐ Right
- ☐ Into the page ☐ Out of the page
- ☐ The direction is undefined since the acceleration is zero.

Justify your answer.