2023

AP

# AP® Physics C: Electricity and Magnetism

## Scoring Guidelines
## Set 2

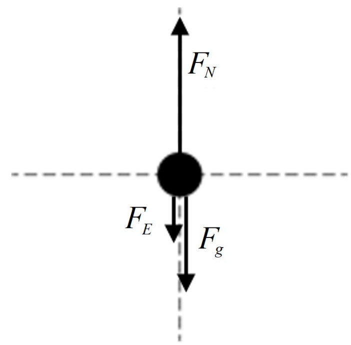
## Question 1: Free-Response Question — 15 points

| | | |
|---|---|---|
| **(a)** | For correctly drawing and labeling the electrostatic force in the downward direction | **1 point** |
| | For drawing the normal force in the upward direction and a gravitational force in the downward direction | **1 point** |

**Scoring Note:** $F_S$ is an acceptable label to represent the force that the platform exerts on the sphere

**Scoring Note:** A maximum of 1 point may be earned if extraneous forces are included.

**Example Response**




**Total for part (a) — 2 points**

**(b)** For applying an equation of the forces at equilibrium consistent with the diagram drawn in part (a) **1 point**

**Example Response**

$$F_N - F_E - F_g = 0$$

For substituting a $k_s x$ or $k_s y$ that represents the normal force **1 point**

**Example Response**

$$k_s x - F_E - F_g = 0$$

For substituting a correct expression that represents the electrostatic force **1 point**

**Example Response**

$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{H^2}$$

For substituting a correct expression that represents the gravitational force **1 point**

**Example Response**

$$F_g = Mg$$

**Example Solution**

$$F_N - F_E - F_g = 0$$

$$F_N = F_E + F_g$$

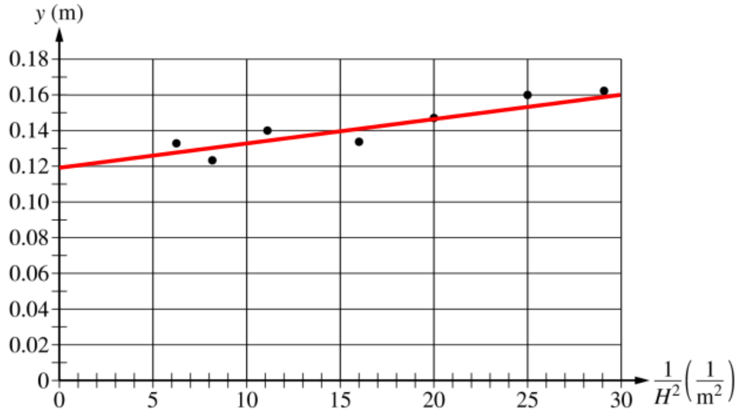
$$k_s y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{H^2} + Mg$$

$$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$$

**Total for part (b) 4 points**

| | | |
|---|---|---|
| **(c)(i)** | For a line that approximates the trend of the data | **1 point** |

**Example Response**



**(c)(ii)** For using two points from the trend line drawn by the student to calculate the slope **1 point**

**Scoring Note:** Points of data may be used only if points of data are located directly on the line.

**Example Response**

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

$$\text{Slope} = \frac{\Delta(y)}{\Delta\left(\frac{1}{H^2}\right)}$$

$$\text{Slope} = \frac{(0.15\text{ m} - 0.12\text{ m})}{\left(20\ \frac{1}{\text{m}^2} - 0\ \frac{1}{\text{m}^2}\right)}$$

$$\text{Slope} = 0.0015\text{ m}^3$$

For indicating the relationship between the slope of the graph to $\varepsilon_0$ in the equation **1 point**

$$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$$

**Example Response**

$$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$$

$$\text{slope} = \left(\frac{Qq}{4\pi\varepsilon_0 k_s}\right)$$

For correctly substituting the value of the slope of the graph and other given quantities into the equation to calculate an experimental value of $\varepsilon_0$ **1 point**

**Scoring Note:** A numerical response without units may earn this point.

**Example Solution**

$$\text{slope} = \frac{Qq}{4\pi\varepsilon_0 k_s}$$

$$\varepsilon_0 = \frac{Qq}{4\pi k_s(\text{slope})}$$

$$\varepsilon_0 = \frac{\left(2\times 10^{-6}\text{ C}\right)^2}{4\pi\left(25\frac{\text{N}}{\text{m}}\right)\left(0.0015\text{ m}^3\right)}$$

$$\varepsilon_0 = 8.5\times 10^{-12}\ \frac{\text{C}^2}{\text{N}\bullet\text{m}^2}$$

| | | |
|---|---|---|
| **(c)(iii)** | For identifying that the $y$-intercept $= \dfrac{Mg}{k_s}$ | **1 point** |
| | For correctly substituting the value of the $y$-intercept of the graph and other given quantities and constants into the equation to calculate an experimental value of $M$<br><br>**Scoring Note:** A numerical response without units may earn this point. | **1 point** |

**Example Response**

$y$-intercept $= 0.12$ m

$$y\text{-intercept} = \frac{Mg}{k_s}$$

$$M = \frac{(0.12 \text{ m})(25 \text{ N/m})}{9.8 \text{ m/s}^2}$$

$$M = 0.30 \text{ kg}$$

**Total for part (c) 6 points**

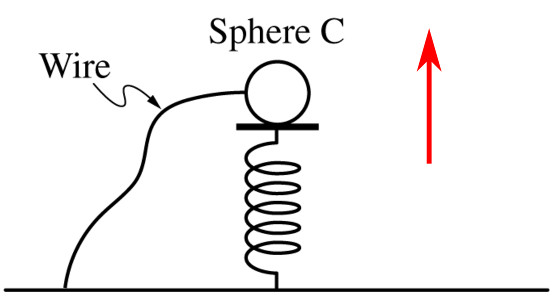
| | | |
|---|---|---|
| **(d)(i)** | For selecting "$y_2 < y_1$" with an attempt at a relevant justification | **1 point** |
| | For a justification that indicates correct charge rearrangement in Sphere C due to electrostatic force from Sphere A | **1 point** |

**Example Response**

*$y_2 < y_1$, Charges are now free to move within Sphere C now that it is a conducting sphere. Electrons on Sphere C will be attracted to the excess positive charges on Sphere A and move closer to Sphere A. This leaves the opposite side of Sphere C more positively charged which results in less electric repulsion between the spheres and as a result less compression in the spring.*

| | | |
|---|---|---|
| **(d)(ii)** | For drawing an upward pointing arrow | **1 point** |

**Example Response**



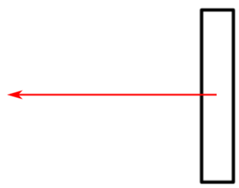

**Total for part (d) 3 points**

**Total for question 1 15 points**

## Question 2: Free-Response Question — 15 points

| | | |
|---|---|---|
| **(a)** | For drawing an arrow pointing to the left with no extraneous arrows | **1 point** |

**Example Response**



| | |
|---|---|
| **Total for part (a)** | **1 point** |

| | | |
|---|---|---|
| **(b)(i)** | For using Faraday's law to calculate the value of the induced emf | **1 point** |

**Scoring Note:** This point may be earned without the negative sign or a numerical answer.

**Example Response**

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$
$$\mathcal{E} = -\frac{d(B_1 dx)}{dt}$$

For a correct substitution of $v$ for $\frac{dx}{dt}$ **1 point**

**Scoring Note:** A student can earn points 1 and 2 of part (b)(i) by starting with the expression $\mathcal{E} = B_1 dv$.

**Example Response**

$$\mathcal{E} = -B_1 d\left(\frac{dx}{dt}\right)$$
$$\mathcal{E} = -B_1 dv$$

For substituting the correct resistance into an equation for Ohm's law to solve for the current **1 point**

**Example Solution**

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$
$$\mathcal{E} = -\frac{d(B_1 dx)}{dt}$$
$$\mathcal{E} = -B_1 d\left(\frac{dx}{dt}\right)$$
$$\mathcal{E} = -B_1 dv$$
$$\mathcal{E} = -(0.40\text{ T})(0.30\text{ m})(2.5\text{ m/s})$$
$$\mathcal{E} = -0.30\text{ V}$$

$$\Delta V = IR$$
$$I = \frac{\Delta V}{R}$$
$$I = \frac{|\mathcal{E}|}{R}$$
$$I = \frac{|-0.30\text{ V}|}{0.20\ \Omega} = 1.5\text{ A}$$

| | | |
|---|---|---|
| **(b)(ii)** | For substituting the current or an expression for the current obtained from part (b)(i) into an appropriate equation for calculating the magnetic force | **1 point** |

**Example Responses**

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$
$$F = IdB_1$$
$$F = (1.5\text{ A})(0.3\text{ m})(0.4\text{ T})$$
$$F = 0.18\text{ N}$$

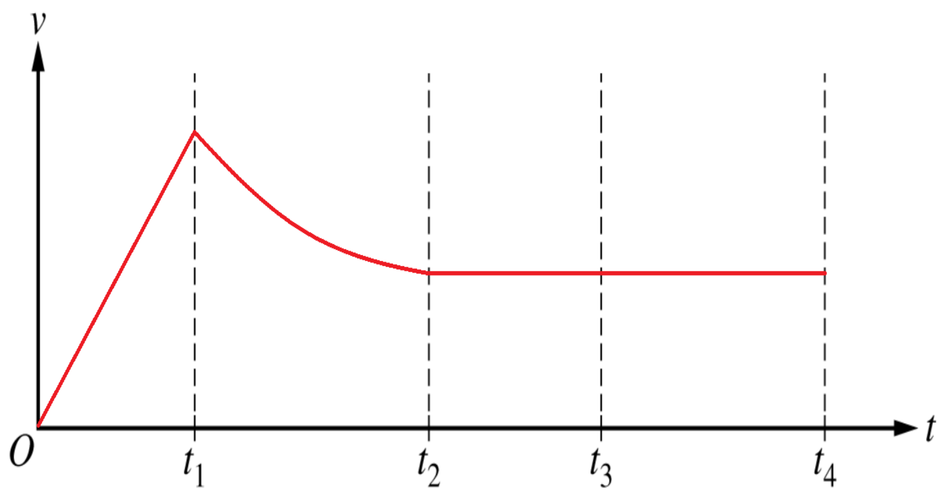
**OR**

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$
$$F = IdB_1$$
$$F = \left(\frac{B_1 d v}{R}\right) dB$$
$$F = \frac{B_1^2 d^2 v}{R}$$
$$F = \frac{(0.4\text{ T})^2 (0.3\text{ m})^2 (2.5\text{ m/s})}{0.2\ \Omega}$$
$$F = 0.18\text{ N}$$

**Total for part (b) 4 points**

| | | |
|---|---|---|
| **(c)** | For drawing a straight line with a positive slope that starts at the origin from $t = 0$ to $t_1$ | **1 point** |
| | For drawing a curve that is decreasing and concave up from $t_1$ to $t_2$ | **1 point** |
| | For drawing a nonzero horizontal line from $t_2$ to $t_3$ | **1 point** |
| | For drawing a nonzero horizontal line from $t_3$ to $t_4$ | **1 point** |

**Example Response**




**Total Points for part (c)** **4 points**

| | | |
|---|---|---|
| **(d)(i)** | For a correct answer with units ( $0.4\ \Omega$ )<br><br>**Scoring Note:** This point can be earned without supporting calculations. | **1 point** |
| | **Example Response**<br><br>$R_s = \sum_i R_i$<br>$R_s = (0.2\ \Omega) + (0.2\ \Omega)$<br>$R_s = 0.4\ \Omega$ | |
| **(d)(ii)** | For a statement that correctly describes the inverse relation between resistance and current (e.g., as resistance increases, current decreases) | **1 point** |
| | For a statement that correctly describes the direct relation between current and force (e.g., as current decreases, magnetic force decreases) | **1 point** |
| | For a statement that correctly describes the direct relation between force and acceleration (e.g., as force decreases acceleration decreases) | **1 point** |
| | **Scoring Note:** Full credit can be earned with a justification that is consistent with the resistance calculated in part (d)(i).<br><br>**Example Response**<br><br>*The new acceleration* $a_{\text{new}}$ *is less than* $a_{\text{original}}$. *Greater resistance of the bar causes the current to be less than in the original scenario. Less current causes the magnetic force* $F = IdB$ *on the bar to also be less than the original. By Newton's second law* $F = ma$ *so less force on a bar of the same mass results in less acceleration.* | |
| | **Total for part (d)** | **4 points** |

| | | |
|---|---|---|
| **(e)** | For correctly indicating **one** of the following, with an attempt at a relevant justification:<br>• Increasing $H$<br>• Increasing $B_1$<br>• Increasing $d$ | **1 point** |
| | For correctly justifying the identified modification that will result in a larger induced current in the new bar at position $x_B$ | **1 point** |

**Example Responses**

*Increasing $H$ will increase the induced current. If the ramp is higher, then the potential energy is greater and this results in greater kinetic energy and greater velocity at the bottom of the ramp. A greater velocity causes a greater rate of change in flux as the bar moves through the field. By Faraday's law the* emf *is greater and therefore also the current.*

**OR**

*Increasing $B_1$ will increase the induced current. If the magnetic field is stronger this increases the flux through the circuit and therefore also the rate of change in the flux. By Faraday's law the* emf *is then greater and therefore also the current.*

**OR**

*Increasing $d$ will increase the induced current. A larger width results in a greater area encompassed by the circuit. Greater area increases the flux through the circuit and therefore also the rate of change in the flux. By Faraday's law the* emf *is then greater and therefore also the current.*

**Total for part (e) 2 points**

**Total for question 2 15 points**

## Question 3: Free-Response Question — 15 points

| | | |
|---|---|---|
| **(a)** | For a loop rule expression that includes terms for the equivalent resistance $2R$ and the potential difference across the battery | **1 point** |
| | For an expression that includes charge $Q$ in the term relating the potential difference across the capacitor and includes charge per unit time $\frac{dQ}{dt}$ in the term relating the potential difference across the pair of resistors | **1 point** |

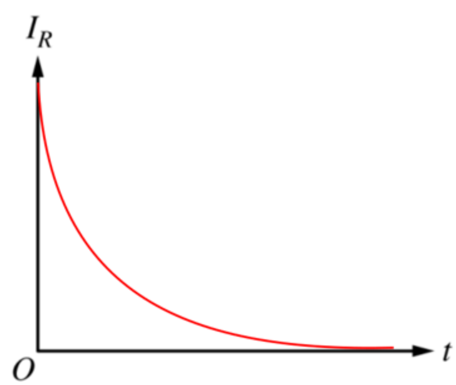
**Example Response**

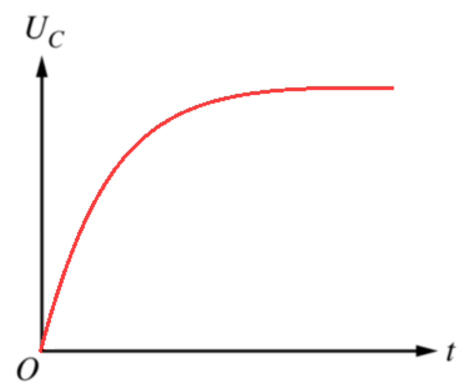
$$\mathcal{E} - \Delta V_C - \Delta V_{R,eq} = 0$$

$$\mathcal{E} - \frac{Q}{C} - 2R\frac{dQ}{dt} = 0$$

| | | |
|---|---|---|
| | **Total for part (a)** | **2 points** |
| **(b)** | For sketching a concave up and decreasing curve on the graph of $I_R$ as a function of $t$ | **1 point** |
| | For sketching a concave down and increasing curve on the graph of $U_C$ as a function of $t$ | **1 point** |
| | For sketching both curves that approach a slope of zero as time increases<br><br>**Scoring Note:** The third point can be earned even if the first two points are not earned. | **1 point** |

**Example Response**




| | | |
|---|---|---|
| | **Total for part (b)** | **3 points** |

**(c)(i)** For a correct justification that could include one of the following: **1 point**

- An indication that the current is upwards that includes a statement that indicates that positive charge had accumulated on the top plate of Capacitor 1 and/or negative charge has accumulated on the bottom plate of Capacitor 1 when the switch was closed to Position A
- An indication that the current is upwards that includes a statement that indicates that the value of the electric potential of the top plate of Capacitor 1 is larger than the electric potential of the bottom plate of Capacitor 1 when the switch was closed to Position A

**Example Responses**

*When the switch is closed at time* $t_1$*, positive charge has built up on the top plate of the capacitor. This positive charge on the top plate pushes charge up through Resistor* 1 *and down through Capacitor* 2 *to charge Capacitor* 2.

**OR**

*After a long-time the top plate of Capacitor* 1 *is at a high potential due to its being charged by the battery. When the switch is closed at time* $t_1$*, the resulting current is up through Resistor* 1 *as the current goes from high potential on the top plate to low potential clockwise around the circuit through Capacitor* 2.

**(c)(ii)** For indicating that the total charge on the positive plate of Capacitor 2 is $\frac{Q_0}{2}$ **1 point**

**Scoring Note:** This point can be earned without supporting calculations.

**Example Response**

*The potential difference across Capacitor* 1 *is equal to the potential difference across Capacitor* 2. *Capacitor* 2 *has the same capacitance of Capacitor* 1. *Therefore, Capacitor* 2 *stores the same charge that is stored on Capacitor* 1. *Due to conservation of charge, Capacitor* 2 *stores half of the original charge equal to* $\frac{Q_0}{2}$.

**(c)(iii)** For indicating that the total energy dissipated by Resistor 1 is the difference between the initial electric potential energy of the system at time $t = t_1$ and the final electric potential energy of the system after the new steady state conditions have been reached **1 point**

**Example Response**

$$\Delta E_R = U_C - U_{0C}$$

For indicating that only Capacitor 1 stores nonzero electric potential energy initially and both capacitors store electric potential energy after the new steady-state conditions have been reached, or an alternate response that is consistent with part (c)(ii) **1 point**

**Example Response**

$$U_{0C} = U_{01} \textbf{ AND } U_C = U_1 + U_2$$

For correct substitutions for the charges stored on the capacitors after the new steady state conditions have been reached based on part (c)(ii) **1 point**

**Example Solution**

$$\Delta E_R = U_C - U_{0C}$$

$$\Delta E_R = \left(\frac{1}{2}\left(\frac{1}{C}\right)\left(\frac{Q_0}{2}\right)^2 + \frac{1}{2}\left(\frac{1}{C}\right)\left(\frac{Q_0}{2}\right)^2\right) - \frac{1}{2}\frac{Q_0^2}{C}$$

$$\Delta E_R = \frac{Q_0^2}{4C} - \frac{1}{2}\frac{Q_0^2}{C}$$

$$\Delta E_R = -\frac{Q_0^2}{4C}$$

**Total for part (c)** **5 points**

**(d)** For the correct expression for charge on the top plate of Capacitor 2 $\left(Q_2 = \dfrac{2Q_0}{3}\right)$ **1 point**

**Example Response**

$$C_1 = C \text{ and } C_2 = \kappa C = 2C$$

$$\Delta V_{C1} = \Delta V_{C2}$$

$$\frac{Q_1}{C_1} = \frac{Q_2}{C_2}$$

$$Q_1 = \frac{1}{2}Q_2$$

$$Q_1 + Q_2 = Q_0$$

$$\frac{1}{2}Q_2 + Q_2 = Q_0$$

$$Q_2 = \frac{2}{3}Q_0$$

**Scoring Note:** This point can be earned without supporting calculations.

**Total for part (d)** **1 point**

**(e)(i)** For a loop rule equation that includes terms for the potential difference across Resistor 2 and the potential difference across Capacitor 2 with the dielectric — **1 point**

**Example Response**

$$\Delta V_{R,2} - \Delta V_{C,2} = 0$$
$$\Delta V_{R,2} = \Delta V_{C,2}$$

For correct substitution of $IR$ for the potential difference across Resistor 2 — **1 point**

**Example Response**

$$\Delta V_{R,2} = IR$$

For correct substitutions of $2C$ for the new capacitance of Capacitor 2 with the dielectric inserted and of the charge consistent with part (d) into the expression for the potential difference across the capacitor — **1 point**

**Example Response**

$$\Delta V_{C,2} = \frac{Q_2}{C_2}$$
$$\Delta V_{C,2} = \left(\frac{2Q_0}{3}\right)\left(\frac{1}{2C}\right)$$

**Example Solution**

$$\Delta V_{R,2} - \Delta V_{C,2} = 0$$
$$\Delta V_{R,2} = \Delta V_{C,2}$$
$$IR = \left(\frac{2Q_0}{3}\right)\left(\frac{1}{2C}\right)$$
$$IR = \frac{Q_0}{3C}$$
$$I = \frac{Q_0}{3RC}$$

**(e)(ii)** For indicating that the current is zero — **1 point**

**Total for part (e)** — **4 points**

**Total for question 3** — **15 points**