Past-paper walk-through

Magnetism and Moving Charges ▪ 12.2

eXercise

Questions in this set

- 2026 Q3
- 2024 Q4
- 2022 Q4
- 2021 Q3
- 2019 Q1
- 2018 Q1
- 2015 Q4

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 3

2026 ▪ Q3

The following information applies to parts A and B.

In Experiment 1, scientists want to collect data that can be graphed to determine the magnitude B_0 of an external, uniform magnetic field. The field is directed into Figure 1 in the region between identical, parallel, conducting plates that are connected to a power supply of variable emf $\mathcal{E}$. The plates are a known distance d apart, where d is much smaller than the dimensions of the plates.

[Figure 1: A power supply (with terminals $+$ and $-$) connected by wires to a rectangular "Device" box, which emits particles with speed v toward the region between two horizontal parallel plates (upper plate labelled at right as "Plate", lower plate unlabeled) separated by a known distance d. Between the plates, an array of "$\times$" symbols indicates a uniform magnetic field B_0 directed into the page. A "Motion

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Detector" (shaded square) is positioned to the right of the plates, in line with the gap between them. Note: Figure not drawn to scale.]
In each trial, a device emits small, charged spheres with speed v through the region between the plates. $\mathcal{E}$ is varied until the spheres move undeflected toward a motion detector. The scientists can vary v between trials. Gravitational effects are negligible.
In addition to the equipment shown in Figure 1, the scientists also have access to a voltmeter. The scientists do not have access to other measuring tools, devices, sensors, or equipment.
(a)(i) Part A
Indicate quantities that could be measured using the available equipment that would allow the scientists to determine B_0 by using a linear graph.
(a)(ii) Briefly **describe** a method to reduce experimental uncertainty for the measured quantities indicated in part A (i).

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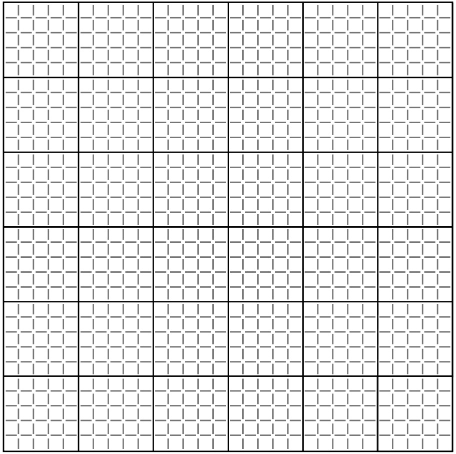

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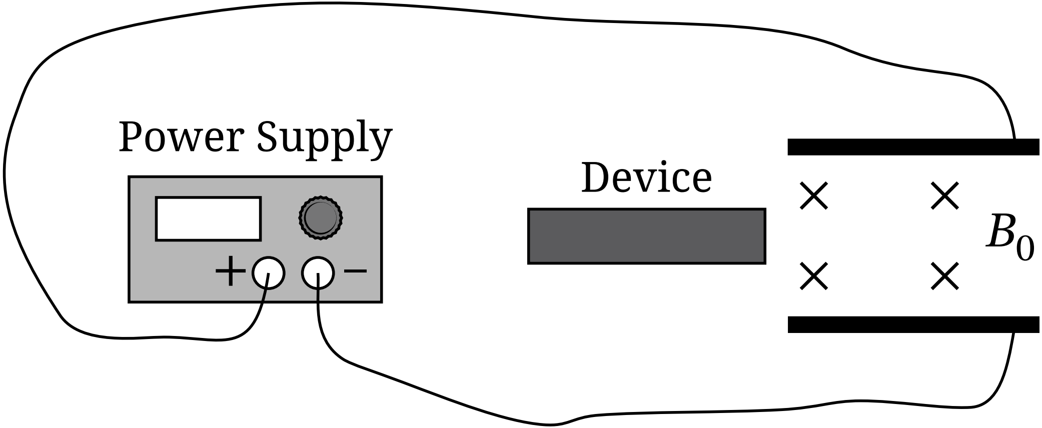

Question 3

Table 1

B (T)	r (m)
0.04	1.8
0.06	1.2
0.14	0.5
0.16	0.4
0.20	0.3

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2026 ▪ Q3

The following information applies to parts A and B.

In Experiment 1, scientists want to collect data that can be graphed to determine the magnitude B_0 of an external, uniform magnetic field. The field is directed into Figure 1 in the region between identical, parallel, conducting plates that are connected to a power supply of variable emf $\mathcal{E}$. The plates are a known distance d apart, where d is much smaller than the dimensions of the plates.

[Figure 1: A power supply (with terminals $+$ and $-$) connected by wires to a rectangular "Device" box, which emits particles with speed v toward the region between two horizontal parallel plates (upper plate labelled at right as "Plate", lower plate unlabeled) separated by a known distance d. Between the plates, an array of "$\times$" symbols indicates a uniform magnetic field B_0 directed into the page. A "Motion Detector" (shaded square) is positioned to the right of the plates, in line with the gap between them. Note: Figure not drawn to scale.]

Question 3

In each trial, a device emits small, charged spheres with speed v through the region between the plates. $\mathcal{E}$ is varied until the spheres move undeflected toward a motion detector. The scientists can vary v between trials. Gravitational effects are negligible.

In addition to the equipment shown in Figure 1, the scientists also have access to a voltmeter.

The scientists do not have access to other measuring tools, devices, sensors, or equipment.

(b)(i) Part B

Indicate what quantities the scientists could graph on the horizontal and vertical axes to create a linear graph that can be used to determine B_0. Clearly indicate which quantity corresponds to each axis.

(b)(ii) Briefly **describe** the relationship between B_0 and one feature of the graph from part B (i). Your answer may include an equation that relates B_0 and the indicated feature of the graph.

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2026 ▪ Q3

The following information applies to parts A and B.

In Experiment 1, scientists want to collect data that can be graphed to determine the magnitude B_0 of an external, uniform magnetic field. The field is directed into Figure 1 in the region between identical, parallel, conducting plates that are connected to a power supply of variable emf $\mathcal{E}$. The plates are a known distance d apart, where d is much smaller than the dimensions of the plates.

[Figure 1: A power supply (with terminals $+$ and $-$) connected by wires to a rectangular "Device" box, which emits particles with speed v toward the region between two horizontal parallel plates (upper plate labelled at right as "Plate", lower plate unlabeled) separated by a known distance d. Between the plates, an array of "$\times$" symbols indicates a uniform magnetic field B_0 directed into the page. A "Motion Detector" (shaded square) is positioned to the right of the plates, in line with the gap between them. Note: Figure not drawn to scale.]

Question 3

In each trial, a device emits small, charged spheres with speed v through the region between the plates. $\mathcal{E}$ is varied until the spheres move undeflected toward a motion detector. The scientists can vary v between trials. Gravitational effects are negligible.

In addition to the equipment shown in Figure 1, the scientists also have access to a voltmeter.

The scientists do not have access to other measuring tools, devices, sensors, or equipment.

(c)(i) The following information applies to parts C and D.

In Experiment 2, scientists want to use a graph to determine the mass m of identical, charged particles that are emitted from a device. Each particle has charge $Q = +6.4 \times 10^{-19}$ C.

In each trial, a particle is emitted with speed $v_0 = 3.0 \times 10^6$ m/s toward a region of external, uniform magnetic field of variable magnitude B. The radius r of the path along which the particle moves while in the field, shown in Figure 2, is recorded.

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[Figure 2: A particle of mass m and charge Q enters from the left with velocity v_0 (dashed horizontal arrow) into a rectangular region filled with dots representing a uniform magnetic field B directed out of the page. Inside the field region, a dashed curved arc (a semicircular path) curves the particle's trajectory, with a double-headed arrow labelled r marking the radius of the circular path.]

In subsequent trials, B is increased and the resulting r is recorded. Gravitational effects are negligible. Collected data are provided in Table 1.

Table 1

B (T)	r (m)
0.04	1.8
0.06	1.2
0.14	0.5
0.16	0.4
0.20	0.3

Part C

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Label the axes of the grid provided with measured or calculated quantities. Include units, as appropriate. The graphed quantities should yield a linear graph that can be used to determine m.

(c)(ii) On the grid, **create** a graph of the quantities indicated in part C (i).

- **Label** the vertical and horizontal axes with numerical scales.
- **Plot** the corresponding data points on the grid.
- Table 2 is provided in your booklet for scratch work, but the table will not be scored.

[A blank labelled grid (square grid ruling) is provided for the student to label axes, choose numerical scales, and plot the data points from Table 1, with blank lines above and below the grid for writing the "Quantity (units, if appropriate)" for each axis.]

(c)(iii) **Draw** a best-fit line for the data graphed in part C (ii).

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The following information applies to parts A and B.

In Experiment 1, scientists want to collect data that can be graphed to determine the magnitude B_0 of an external, uniform magnetic field. The field is directed into Figure 1 in the region between identical, parallel, conducting plates that are connected to a power supply of variable emf $\mathcal{E}$. The plates are a known distance d apart, where d is much smaller than the dimensions of the plates.

[Figure 1: A power supply (with terminals $+$ and $-$) connected by wires to a rectangular "Device" box, which emits particles with speed v toward the region between two horizontal parallel plates (upper plate labelled at right as "Plate", lower plate unlabeled) separated by a known distance d. Between the plates, an array of "$\times$" symbols indicates a uniform magnetic field B_0 directed into the page. A "Motion Detector" (shaded square) is positioned to the right of the plates, in line with the gap between them. Note: Figure not drawn to scale.]

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In each trial, a device emits small, charged spheres with speed v through the region between the plates. $\mathcal{E}$ is varied until the spheres move undeflected toward a motion detector. The scientists can vary v between trials. Gravitational effects are negligible.

In addition to the equipment shown in Figure 1, the scientists also have access to a voltmeter.

The scientists do not have access to other measuring tools, devices, sensors, or equipment.

(d) Part D

Calculate m from the best-fit line drawn on the grid.

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2024 ▪ Q4

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(a) **Calculate** the ratio $\frac{K_2}{K_1}$.

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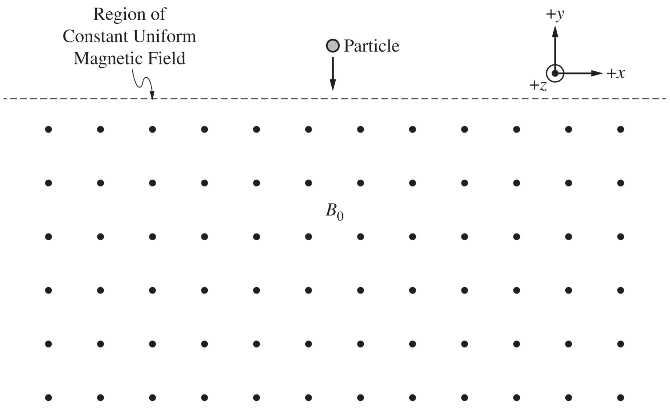

Figure 2

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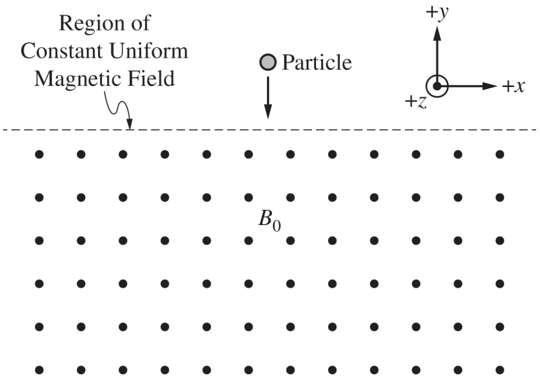

Figure 1

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Two particles, 1 and 2, have different mass and charge as described by the following.

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In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(b)(i) [Figure 1: A diagram showing a "Region of Constant Uniform Magnetic Field" as a grid of dots (indicating a field directed out of the page, in the $+z$-direction) bounded above by a dashed horizontal line. Above the region, a "Particle" (circle with

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dot) is shown with a downward arrow into the region. A small coordinate axis in the upper right shows $+y$ up, $+x$ right, and $+z$ out of the page (toward viewer). The field magnitude is labeled B_0 within the dotted region.]

After exiting the device, the particles enter a large region of constant uniform magnetic field of magnitude B_0 that is directed in the $+z$-direction (out of the page), as shown in Figure 1. Each particle is moving in the $-y$-direction when entering the region, and each particle is moving in the $+y$-direction when exiting the region.

Determine an expression for the speed of Particle 2 in the region. Express your answer in terms of M, K_2, and physical constants, as appropriate.

(b)(ii) **Derive** an expression for the horizontal distance Δx between the locations where Particle 2 enters and leaves the region. Express your answer in terms of M, Q, K_2, B_0, and physical constants, as appropriate.

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2024 ▪ Q4

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\dfrac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(c) [Figure 2: The same diagram as Figure 1 — a "Region of Constant Uniform Magnetic Field" shown as a grid of dots bounded above by a dashed horizontal line, with a "Particle" (circle with dot) above the region and a downward arrow into it, and

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the coordinate axis ($+y$ up, $+x$ right, $+z$ out of page) shown in the upper right, field magnitude B_0 labeled within the region. This copy is provided blank for the student to sketch on.]

On the following diagram in Figure 2, **sketch** and clearly **label** the paths of **both** particles 1 and 2 in the region.

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Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(d) A uniform electric field is added to the region such that Particle 1 of negative charge $-Q$ travels with constant speed in a straight line through the region.

Determine the direction of the electric field.

Solution 4

(a) Mark scheme

- $K_2/K_1 = 2$. Derivation: for a charged particle released from rest and accelerated through a potential difference ΔV, energy conservation ($E_0 = E_f$, $\Delta U + \Delta K = 0$) gives $-\Delta U_E = \Delta K$, i.e. the final kinetic energy equals $|q\Delta V|$. Particle 1 (charge $-Q$): $K_1 = |-Q\Delta V| = Q\Delta V$. Particle 2 (charge $+2Q$, same ΔV): $K_2 = |+2Q\Delta V| = 2Q\Delta V$. Ratio: $\dfrac{K_2}{K_1} = \dfrac{2Q\Delta V}{Q\Delta V} = 2$. Scoring: 1 pt for indicating the final kinetic energy of a particle equals $|q\Delta V|$ (explicit absolute-value notation not required); 1 pt for the correct ratio $K_2/K_1 = 2$.

Solution 4

(b)(i) Mark scheme

- $v = 2\sqrt{\dfrac{K_2}{M}}$. Derivation: kinetic energy $K = \frac{1}{2}mv^2$. Particle 2 has mass $M/2$, so $K_2 = \frac{1}{2}\left(\dfrac{M}{2}\right)v^2$. Solving for v: $v = 2\sqrt{K_2/M}$. Scoring: 1 pt for a correct expression for the speed of Particle 2 in terms of K_2 and M.

Solution 4

(b)(ii) Mark scheme

- $\Delta x = \dfrac{\sqrt{K_2 M}}{QB_0}$. Derivation: Newton's second law with the magnetic force gives $\vec{a}_c = \dfrac{q\vec{v} \times \vec{B}}{m}$, so for circular motion $\dfrac{v^2}{r} = \dfrac{qvB}{m}$, i.e. $r = \dfrac{mv}{qB}$. Substituting Particle 2's mass $(M/2)$, charge magnitude $(2Q)$, speed from part (b)(i) $\left(v = 2\sqrt{K_2/M}\right)$, and field B_0: $r = \dfrac{(M/2)\left(2\sqrt{K_2/M}\right)}{2QB_0} = \dfrac{\sqrt{K_2 M}}{2QB_0}$. The horizontal distance Δx between where the particle enters and leaves the field region equals the diameter of the semicircular path: $\Delta x = 2r = \dfrac{\sqrt{K_2 M}}{QB_0}$. Scoring: 1 pt for substituting the

Solution 4

magnetic-force expression into a Newton's-second-law equation for circular motion; 1 pt for correctly substituting Particle 2's mass, charge, and speed (from (b)(i)) into the resulting radius expression; 1 pt for indicating $\Delta x = 2r$.

Solution 4

(c) Mark scheme

- Sketch (both particles enter moving straight down into the field region and curve back out): Particle 1's path is a semicircular arc that is concave up and curves to the right, with a LARGER radius of curvature. Particle 2's path is a semicircular arc that is concave up and curves to the left — the opposite direction from Particle 1 (consistent with its opposite-sign charge) — with a SMALLER radius of curvature than Particle 1's path (consistent with Particle 2's smaller mass and larger charge magnitude giving a smaller $r = mv/qB$). Scoring: 1 pt for a path for Particle 1 that is concave up and to the right; 1 pt for a path for Particle 2 that is concave up and in the opposite direction from Particle 1; 1 pt for Particle 1's path having a larger radius of curvature than Particle 2's path.

Solution 4

(d) Mark scheme

- The electric field must point in the $+x$-direction. Reasoning: Particle 1 carries charge $-Q$ and must travel in a straight line at constant speed through the region, so the electric force $q\vec{E}$ must exactly cancel the magnetic force on it at every instant; given the curving direction of Particle 1's path shown in part (c) (curving to the right, i.e. toward $+x$, under the magnetic force), the needed electric force — and hence, since the charge is negative, the field direction — works out to $+x$. (Any direction consistent with the student's own path for Particle 1 in part (c) also earns credit.) Scoring: 1 pt for indicating either that the electric field is directed in the $+x$-direction, or a direction consistent with the path drawn for Particle 1 in part (c).

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2022 ▪ Q4

[Diagram: A long straight horizontal wire carrying current I directed to the left (shown with a dashed line and an arrow labeled I pointing left). Above the wire, at a distance d, is a dot representing a charged object. Two force vectors are drawn from the dot: F_M pointing straight up, and F_E pointing straight down (toward the wire). A velocity vector v points to the left from the charged object.]

At the instant shown above, a negatively charged object is moving to the left with constant velocity v near a long, straight wire that has a current I directed to the left. The region contains a uniform electric field of magnitude E, and the charged object is at a distance d from the wire. The figure shows the electric and magnetic forces, F_E and F_M, respectively, exerted on the charged object.

(a) Derive an expression for v in terms of E, d, I, and physical constants, as appropriate.

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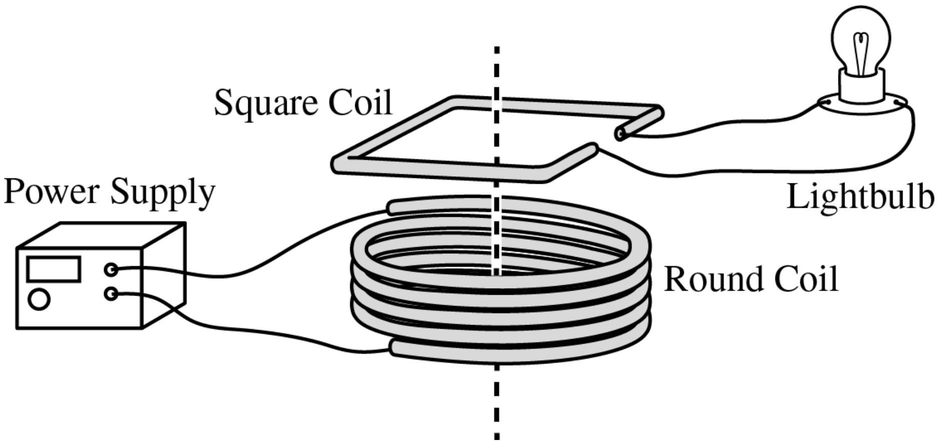

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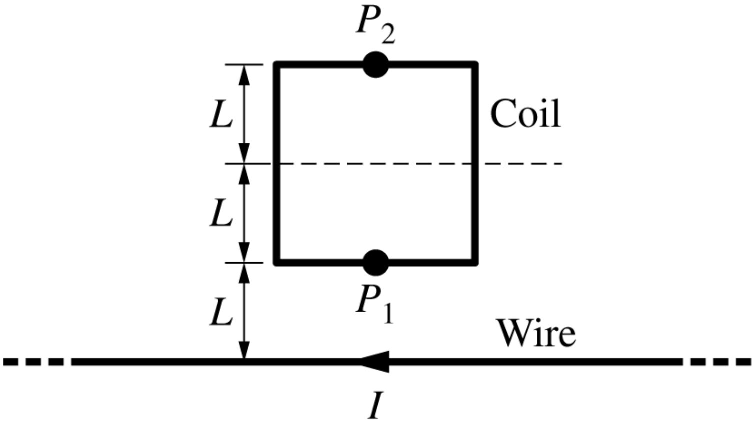

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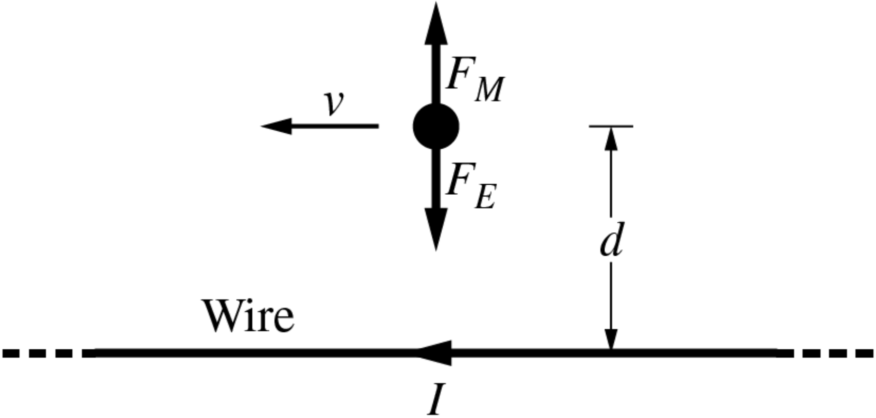

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[Diagram: A long straight horizontal wire carrying current I directed to the left (shown with a dashed line and an arrow labeled I pointing left). Above the wire, at a distance d, is a dot representing a charged object. Two force vectors are drawn from the dot: F_M pointing straight up, and F_E pointing straight down (toward the wire). A velocity vector v points to the left from the charged object.]

At the instant shown above, a negatively charged object is moving to the left with constant velocity v near a long, straight wire that has a current I directed to the left. The region contains a uniform electric field of magnitude E, and the charged object is at a distance d from the wire. The figure shows the electric and magnetic forces, F_E and F_M, respectively, exerted on the charged object.

(b)(i)(n)(t)(r)(o) [Diagram: The charged object has been removed. A square coil labeled "Coil" with side length $2L$ is shown above the same long straight wire carrying

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current I (dashed line, arrow pointing left). The bottom side of the coil is a distance L above the wire; a point P_1 is marked on the bottom side of the coil, and a point P_2 is marked on the top side of the coil. Vertical distance markers show L from the wire to the bottom of the coil, and L for each half of the coil's height (labeled L, L, L from the wire up to P_2), with a horizontal dashed midline shown across the coil.]

The charged object is removed, and a square coil with side length $2L$ is placed near the long, straight wire, as shown above. The bottom of the coil is a distance L from the wire. The magnitude of the magnetic field due to the current in the wire is $3B_0$ at point P_1 and B_0 at point P_2.

(b)(i) Write an "X" at a location on the figure where the magnitude of the magnetic field is $2B_0$. Briefly justify your reasoning.

(b)(ii) Over a time interval of 2.0 s, the current in the wire is decreased. The initial magnetic flux through the coil is 5.0×10^{-5} T $\cdot$ m^2 and the final magnetic flux through

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the coil is 1.0×10^{-5} T $\cdot$ m^2. The coil has a total resistance of 10 Ω. Calculate the magnitude of the average current in the coil during the 2.0 s time interval.

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[Diagram: A long straight horizontal wire carrying current I directed to the left (shown with a dashed line and an arrow labeled I pointing left). Above the wire, at a distance d, is a dot representing a charged object. Two force vectors are drawn from the dot: F_M pointing straight up, and F_E pointing straight down (toward the wire). A velocity vector v points to the left from the charged object.]

At the instant shown above, a negatively charged object is moving to the left with constant velocity v near a long, straight wire that has a current I directed to the left. The region contains a uniform electric field of magnitude E, and the charged object is at a distance d from the wire. The figure shows the electric and magnetic forces, F_E and F_M, respectively, exerted on the charged object.

(c) [Diagram: A power supply connects via wires to a round coil of wire. A square coil is positioned directly above and concentric with the round coil, oriented horizontally

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with a dashed vertical axis line through the center of both coils. A part of the square coil is cut/removed, and the two ends from that gap are connected by wires to a lightbulb, which is shown lit.]
The wire is removed and the square coil is positioned so that the coil is directly above and concentric with a round coil of wire connected to a power supply. A part of the square coil is removed and a lightbulb is connected to the coil, as shown above.
During a short time interval, the current in the power supply is constantly increasing.
Use physics principles to explain why the lightbulb is lit during the entire time interval.

Solution 4

(a) Mark scheme

- (1 point) Set the magnetic force equal to the electric force (velocity selector, zero net force), an appropriate use of Newton's laws: $\Sigma F = ma = 0 \Rightarrow F_M - F_E = 0 \Rightarrow F_M = F_E$. (1 point) Use correct force expressions: $qvB = qE$. (1 point) Substitute the magnetic field of a long straight wire, $B = \dfrac{\mu_0 I}{2\pi d}$, to get an expression including v and the given quantities: $v\left(\dfrac{\mu_0 I}{2\pi d}\right) = E \Rightarrow v = \dfrac{2\pi d E}{\mu_0 I}$.

Solution 4

(b)(i)(n)(t)(r)(o)

Mark scheme

- Introductory/diagram-description text only — no scorable response required. Describes that the charged object has been removed and a square coil of side $2L$ is positioned above the same long straight current-carrying wire, with the coil's bottom side a distance L above the wire, point P_1 marked on the bottom side, and point P_2 marked on the top side (distance $2L$ from the wire). Sets up parts (b)(i) and (b)(ii).

Solution 4

(b)(i) Mark scheme

- (1 point) Mark an "X" on the figure at a location strictly between point P_1 (distance L from the wire) and the coil's dashed centerline (distance $1.5L$ from the wire) — i.e. between L and $1.5L$ from the wire, where the field equals $2B_0$. (1 point) Justify using $B \propto 1/r$ for a long straight wire. Model response: "Magnetic field is inversely proportional to the distance from a long, straight current carrying wire: $B = \dfrac{\mu_0 I}{2\pi r}$. Doubling the distance from the wire from L to $2L$ would reduce the magnetic field from $3B_0$ to $1.5B_0$. Therefore, the magnetic field would be equal to $2B_0$ somewhere between L and $2L$."

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(b)(ii) Mark scheme

- (1 point) Use the change in flux, with correct substitutions, to determine the magnitude of the emf (an independent numerical value for emf is not required to earn later points):
  $$|\mathcal{E}| = \left|-\frac{\Delta\Phi_B}{\Delta t}\right| = \frac{(5.0\times10^{-5} - 1.0\times10^{-5})\ \mathsf{T}\cdot\mathsf{m}^2}{2.0\ \mathsf{s}} = 2.0\times10^{-5}\ \mathsf{V}.\ \text{(1 point)}$$
  Correctly apply Ohm's law with correct substitutions:
  $$I = \frac{|\mathcal{E}|}{R} = \frac{2.0\times10^{-5}\ \mathsf{V}}{10\ \Omega} = 2.0\times10^{-6}\ \mathsf{A}.$$

Solution 4

(c) Mark scheme

- Coherent explanation earning 3 points for indicating: (1 point) the current in the round coil produces a magnetic field; (1 point) that magnetic field from the round coil produces a flux through the square coil; (1 point) the changing flux (as the power-supply current, and hence the round coil's field, changes) produces an emf/current in the square coil circuit throughout the entire interval (a response saying the flux only changes during part of the interval does not earn this point). Model response: "The current in the round coil produces a magnetic field. The magnetic field from the round coil passes through the square coil, producing a flux. As the current in the power supply increases, so does the current in the round coil, and, therefore, the magnetic field created by the current increases.

Solution 4

Since the magnetic field changes, the flux through the square coil changes. The constantly changing magnetic flux through the square coil produces an emf and, therefore, current in the square coil to light the lightbulb."

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2021 ▪ Q3

[Graph 1: axes with B (vertical) vs. I (horizontal). Dashed horizontal lines at B_1 (labeled "B_1 (Out of Page)") and at $-B_1$ (labeled "$-B_1$ (Into Page)"), with corresponding dashed vertical lines at I_1 and $-I_1$. A straight line of positive slope passes through the origin O and through the points $(-I_1, -B_1)$ and (I_1, B_1).]
An electromagnet produces a magnetic field that is uniform in a certain region and zero outside that region. The graph above represents the field as a function of the current in the electromagnet, with positive field directed out of the page and negative field directed into the page.
[Diagram: an upward-pointing arrow labeled "Velocity" and a leftward-pointing arrow labeled "F_B", both attached to a point labeled "Particle".]
(a) The current in the electromagnet is set at $0.5I_1$. When a charged particle in the region moves toward the top of the page, the force exerted on it by the field is F_B

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toward the left, as shown above. What changes to the current in the electromagnet could make the magnitude of the force exerted on the particle equal to $2F_B$ and the direction of the force to the right? Support your answer using physics principles.

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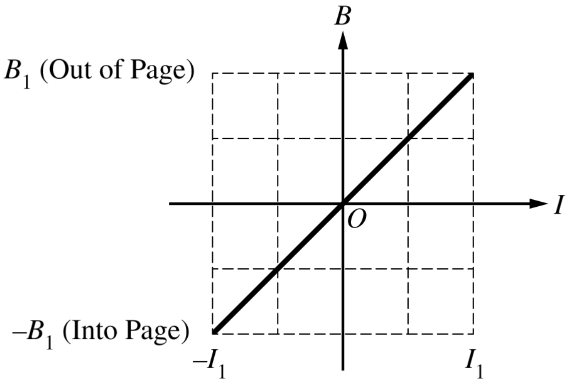

Graph 1

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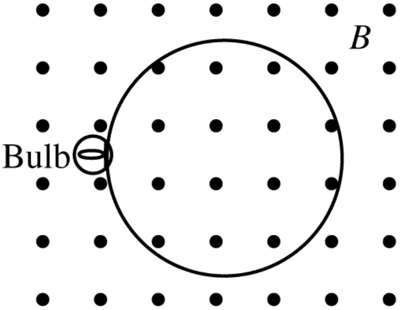
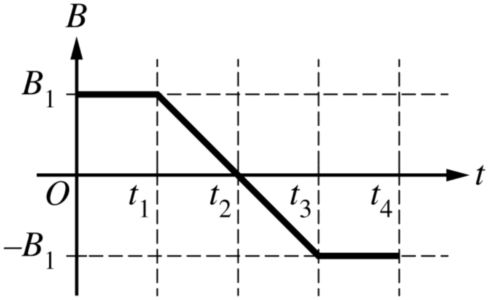
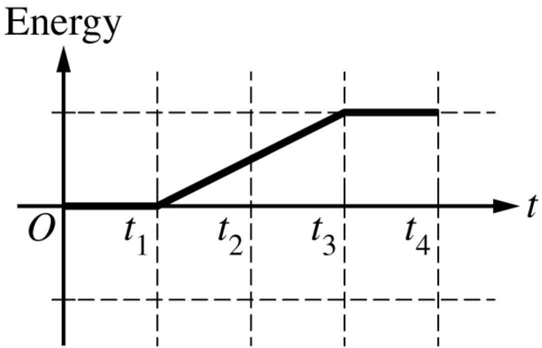




Graph 2

Question 3



Graph 3

Question 3

2021 ▪ Q3

[Graph 1: axes with B (vertical) vs. I (horizontal). Dashed horizontal lines at B_1 (labeled "B_1 (Out of Page)") and at $-B_1$ (labeled "$-B_1$ (Into Page)"), with corresponding dashed vertical lines at I_1 and $-I_1$. A straight line of positive slope passes through the origin O and through the points $(-I_1, -B_1)$ and (I_1, B_1).]
An electromagnet produces a magnetic field that is uniform in a certain region and zero outside that region. The graph above represents the field as a function of the current in the electromagnet, with positive field directed out of the page and negative field directed into the page.
[Diagram: an upward-pointing arrow labeled "Velocity" and a leftward-pointing arrow labeled "F_B", both attached to a point labeled "Particle".]

(b) [Diagram: a circular loop of wire containing a grid of dots (representing a magnetic field out of the page), with a circle labeled "Bulb" on the left side of the loop, and an arrow labeled "B" pointing to the top-right of the loop's boundary.

Question 3

Graph 2: axes with B_1 (vertical, dashed line above origin) vs. t (horizontal), with dashed vertical lines at t_1, t_2, t_3, t_4 and a dashed horizontal line at $-B_1$ below the origin. The plotted curve starts at B_1 for $t < t_1$, decreases linearly crossing zero and continuing down to $-B_1$ by t_2, remains constant at $-B_1$ from t_2 to t_3, then increases linearly back up to B_1 by t_4 and remains constant at B_1 after t_4.
Graph 3: axes with Energy (vertical) vs. t (horizontal), with dashed vertical lines at t_1, t_2, t_3, t_4. The plotted curve is flat (zero slope, cumulative energy constant) for $t < t_1$, then rises with increasing (concave-up) slope from t_1 to t_2, continues rising linearly (constant slope) from t_2 to t_3, then flattens out (zero slope, constant) after t_3 through t_4 and beyond.]
A circuit is made by connecting an ohmic lightbulb of resistance R and a circular loop of area A made of a wire with negligible resistance. The circuit is placed with the plane of the loop perpendicular to the field of the electromagnet, as shown above on the left.

Question 3

The magnetic field changes as a function of time, as shown in Graph 2. The bulb dissipates energy during the interval $t_1 < t < t_3$. Graph 3 below shows the cumulative energy dissipated by the bulb (the total energy dissipated since $t = 0$) as a function of time.

The original bulb is replaced by a new ohmic lightbulb with a greater resistance, but everything else stays the same. How would the cumulative energy graph for the new bulb be different, if at all, from Graph 3 above? Support your answer using physics principles.

Question 3

2021 ▪ Q3

[Graph 1: axes with B (vertical) vs. I (horizontal). Dashed horizontal lines at B_1 (labeled "B_1 (Out of Page)") and at $-B_1$ (labeled "$-B_1$ (Into Page)"), with corresponding dashed vertical lines at I_1 and $-I_1$. A straight line of positive slope passes through the origin O and through the points $(-I_1, -B_1)$ and (I_1, B_1).]

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[Diagram: an upward-pointing arrow labeled "Velocity" and a leftward-pointing arrow labeled "F_B", both attached to a point labeled "Particle".]

(c) The new lightbulb is removed and replaced by the original lightbulb. The magnetic field now changes from $2B_1$ to $-2B_1$ during the same interval $t_1 < t < t_3$. A new

Question 3

cumulative energy graph is created for this situation. How would the new graph be different, if at all, from Graph 3? Support your answer using physics principles.

Question 3

2021 ▪ Q3

[Graph 1: axes with B (vertical) vs. I (horizontal). Dashed horizontal lines at B_1 (labeled "B_1 (Out of Page)") and at $-B_1$ (labeled "$-B_1$ (Into Page)"), with corresponding dashed vertical lines at I_1 and $-I_1$. A straight line of positive slope passes through the origin O and through the points $(-I_1, -B_1)$ and (I_1, B_1).]

An electromagnet produces a magnetic field that is uniform in a certain region and zero outside that region. The graph above represents the field as a function of the current in the electromagnet, with positive field directed out of the page and negative field directed into the page.

[Diagram: an upward-pointing arrow labeled "Velocity" and a leftward-pointing arrow labeled "F_B", both attached to a point labeled "Particle".]

(d) A student derives the following expression for the cumulative energy dissipated by the original bulb during the interval $t_1 < t < t_3$ and with the original change in magnetic field shown in Graph 2.

Question 3

$$\text{Energy} = \frac{A^2 B_1 R}{4(t_3 - t_1)}$$

Whether or not the equation is correct, does the functional dependence of cumulative energy on the elapsed time $(t_3 - t_1)$ make physical sense? Support your answer using physics principles.

Solution 3

(a) Mark scheme

- Since the magnetic force on a moving charge is $F = qvB$, doubling the force magnitude (to 2F_B) at the same particle speed requires doubling the magnetic field magnitude B (1 point). From the given current–field graph, doubling the current doubles the magnetic field, so the current magnitude must also be doubled — the explanation must contain no incorrect statements (1 point). To reverse the force direction (from left to right) while the particle's velocity is unchanged, the magnetic field direction must reverse, which requires reversing the current direction, i.e. making the current negative relative to its original direction (1 point).

Solution 3

(b) Mark scheme

- The induced emf is unchanged when the lightbulb is swapped, since emf depends only on the rate of change of magnetic flux through the loop, which is unchanged (1 point). The new bulb has larger resistance, so for the same emf, $P = \mathrm{emf}^2/R$ (or $I = \mathrm{emf}/R$, $P = I^2R$) gives less current and less power dissipated — explanation must contain no incorrect statements (1 point). Since the slope of the cumulative-energy-vs-time graph represents power, the new graph's slope between t and t is smaller than in Graph 3 (the horizontal line segment after t would lie below the one shown) (1 point).

Solution 3

(c) Mark scheme

- Changing the magnetic field from $2B$ to $-2B$ (a magnitude-$4B$ change) over the same time interval $t < t < t$ is a greater change in magnetic flux than before, producing a larger induced emf ($|\mathrm{emf}| = |\Delta\Phi/\Delta t|$, by Faraday's law) (1 point). Since dissipated power is proportional to the square of the emf ($P = \mathrm{emf}^2/R$), the larger emf means more power and more energy dissipated over the same interval — or an answer consistent with the first point (1 point). Therefore the slope of the new cumulative-energy-vs-time graph between t and t is GREATER than in Graph 3 (the horizontal line segment at the right would lie above the one shown), or an answer consistent with the first point (1 point).

Solution 3

(d) Mark scheme

- For the expression Energy $= A^2B\ R\ /\ [4(t - t\ )]$ to make sense, the cumulative energy dissipated must depend on the elapsed time $(t - t\ )$ in some way — any indication of this dependence earns credit (1 point). Physically, induced emf depends on the RATE of change of magnetic flux, so a larger elapsed time (slower change) gives a SMALLER emf, i.e. emf is inversely proportional to the elapsed time (1 point). Since power is proportional to emf squared ($P \propto \text{emf}^2$) and energy is power times time (Energy $= P \cdot \Delta t$), energy should scale as $(1/\Delta t)^2 \cdot \Delta t = 1/\Delta t$, i.e. energy should be inversely proportional to the elapsed time — NOT directly proportional to it as the student's expression (which has Energy $\propto (t - t\ )$ in the denominator inverted incorrectly / does not reflect a $1/\Delta t$ dependence)

Solution 3

suggests; a correct expression would decrease, not increase, as $(t - t\ )$ grows only if it truly varies as $1/(t - t\ )$ (1 point).

Question 1

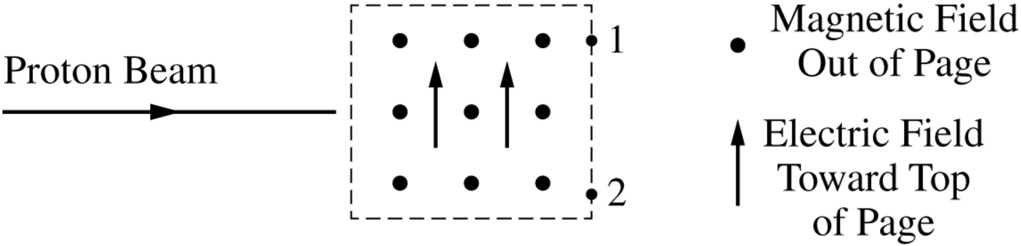
2019 ▪ Q1

The figure above shows a particle with positive charge $+Q$ traveling with a constant speed v_0 to the right and in the plane of the page. The particle is approaching a region, shown by the dashed box, that contains a constant uniform field. The effects of gravity are negligible.
[Figure: A diagram labeled "Region of Field" shows a dashed square box on the right. To the left, a dot labeled "Particle" with "$+Q$" beneath it has an arrow labeled v_0 pointing right toward the box.]
(a)(i) On the figure below, draw a possible path of the particle in the region if the region contains only an electric field directed toward the bottom of the page.
[Figure labeled "Electric Field": a dashed square box on the right; to the left, a dot with an arrow pointing right toward the box.]

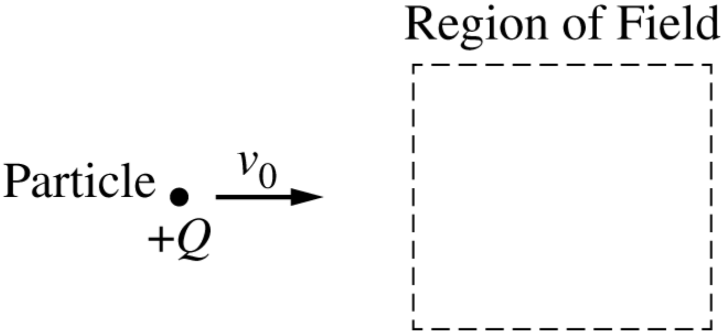
Question 1

(a)(ii) On the figure below, draw a possible path of the particle in the region if the region contains only a magnetic field directed out of the page.
[Figure labeled "Magnetic Field": a dashed square box on the right; to the left, a dot with an arrow pointing right toward the box.]
(a)(iii) For which of the previous situations is the motion more similar to that of a projectile in only a gravitational field near Earth's surface, and why?

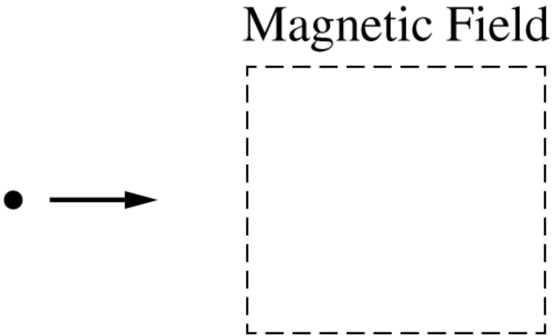
Question 1


Proton Beam
1
2
Magnetic Field
Out of Page
Electric Field
Toward Top
of Page

Question 1



Question 1



Question 1

2019 ▪ Q1

The figure above shows a particle with positive charge $+Q$ traveling with a constant speed v_0 to the right and in the plane of the page. The particle is approaching a region, shown by the dashed box, that contains a constant uniform field. The effects of gravity are negligible.

[Figure: A diagram labeled "Region of Field" shows a dashed square box on the right. To the left, a dot labeled "Particle" with "$+Q$" beneath it has an arrow labeled v_0 pointing right toward the box.]

(b) Another region of space contains an electric field directed toward the top of the page and a magnetic field directed out of the page. Both fields are constant and uniform. A horizontal beam of protons with a variety of speeds enters the region, as shown above. Protons exit the region at a variety of locations, including points 1 and 2 shown on the figure. In a coherent, paragraph-length response, explain why some

Question 1

protons exit the region at point 1 and others exit at point 2. Use physics principles to explain your reasoning.

[Figure: "Proton Beam" with an arrow entering a dashed square box from the left. Inside the box, rows of dots (field out of page) with two upward arrows in the middle (electric field direction inside region); the right edge of the box has two exit points marked "1" (upper) and "2" (lower). To the right of the box, a legend shows a dot labeled "Magnetic Field Out of Page" and an upward arrow labeled "Electric Field Toward Top of Page".]

Solution 1

(a)(i)

Mark scheme

- The particle's path is a curved (parabola-like) trajectory: it starts moving horizontally to the right with no leftward velocity component, then deflects toward the bottom of the page and reaches an edge of the region — analogous to projectile motion, since the electric force $\vec{F} = q\vec{E}$ on the positive charge is constant and directed toward the bottom of the page. Points: 1 pt for a curved path that is initially horizontal and does not have a component of velocity toward the left; 1 pt for a path that deflects toward the bottom of the page and reaches an edge of the region.

Solution 1

(a)(ii) Mark scheme

- For the positive charge moving right through a field directed out of the page, the magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ initially points toward the bottom of the page and continuously changes direction (always perpendicular to velocity), curving the particle along a circular arc that deflects toward the bottom of the page and exits through an edge of the region, without completing more than a semicircle. Points: 1 pt for a curved path that is initially horizontal, is not more than a semicircle, and reaches an edge of the region; 1 pt for a path that deflects toward the bottom of the page.

Solution 1

(a)(iii)

Mark scheme

- The motion in the electric-field case (part (a)(i)) is more similar to projectile motion near Earth's surface, because the electric force (and thus acceleration) on the particle is constant in magnitude and direction — always directed toward the bottom of the page — just as gravity produces a constant downward acceleration on a projectile; both produce a parabolic path. (The magnetic force, by contrast, continually changes direction since it depends on velocity, so it does not give this parabolic analogy.)

Solution 1

(b) Mark scheme

- In this region the electric force on a proton ($F_E = qE$, directed toward the top of the page, since E points that way) and the magnetic force ($F_B = qvB$, directed toward the bottom of the page for a proton moving right through a field out of the page) initially act in opposite directions. F_E does not depend on the proton's speed, but F_B increases with speed. For one particular speed the two forces balance and the proton passes through undeflected; a slower proton has a smaller magnetic force than electric force, so the net force is upward and it deflects upward, exiting at point 1; a faster proton has a larger magnetic force, so the net force is downward and it deflects downward, exiting at point 2. Thus slower protons exit the region at point 1 and faster protons exit at point 2, because the

Solution 1

different net force (sum of the two field forces) produces different paths. Scoring (1 pt each): (1) initially the electric and magnetic forces act in opposite directions; (2) the magnetic force is affected by speed but the electric force is not; (3) different paths occur as a result of the addition (sum) of the forces; (4) slower protons exit higher at point 1 and faster protons exit lower at point 2; (5) a logical, relevant, internally consistent paragraph-length argument that addresses the question using physics principles.

Question 1

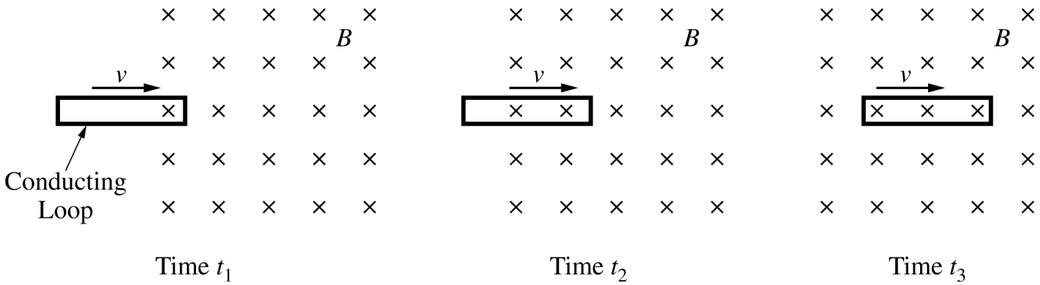
2018 ▪ Q1

The figures above show a rectangular conducting loop at three instants in time. The loop moves at a constant speed v into and through a region of constant, uniform magnetic field B directed into the page. The magnetic field is zero outside the region. [Three diagrams, each showing a grid of "$\times$" symbols (magnetic field B into the page) with a rectangular conducting loop moving to the right with velocity v. "Time t_1": the loop is entering the field region from the left, with its right edge just inside the field and its left edge outside the field (only partially inside the $\times$'s). "Time t_2": the loop is fully inside the field region, entirely surrounded by $\times$'s. "Time t_3": the loop is exiting the field region on the right side, with its left edge inside the field ($\times$'s) and its right edge outside the field (no $\times$'s). Label "Conducting Loop" points to the rectangle at Time t_1.]

Question 1

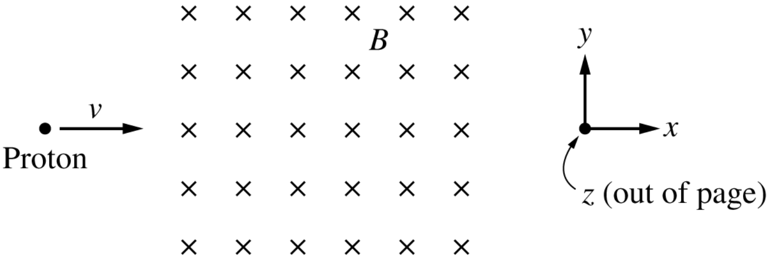
(a) In a coherent paragraph-length response, compare the magnitude and direction of the current at times t_1, t_2, and t_3. Include an explanation of why there is or is not a current and the direction of the current if one is present. Use fundamental physics concepts and principles in your explanation.

Question 1

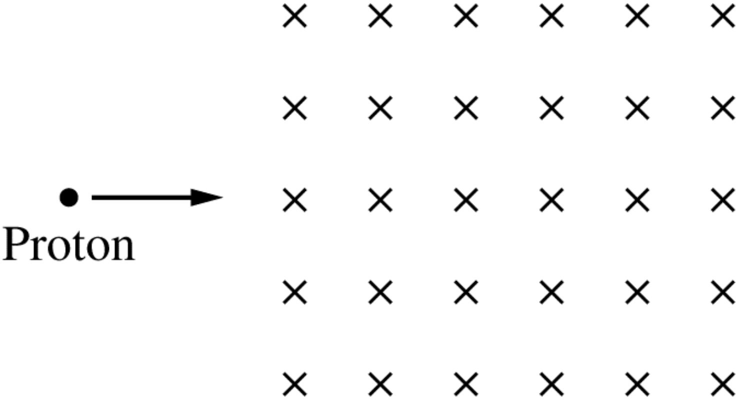


Question 1

of gravity are negligible.



Question 1



Question 1

2018 ▪ Q1

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[Three diagrams, each showing a grid of "$\times$" symbols (magnetic field B into the page) with a rectangular conducting loop moving to the right with velocity v. "Time t_1": the loop is entering the field region from the left, with its right edge just inside the field and its left edge outside the field (only partially inside the $\times$'s). "Time t_2": the loop is fully inside the field region, entirely surrounded by $\times$'s. "Time t_3": the loop is exiting the field region on the right side, with its left edge inside the field ($\times$'s) and its right edge outside the field (no $\times$'s). Label "Conducting Loop" points to the rectangle at Time t_1.]

Question 1

(b)(i) The loop is removed. A proton traveling to the right in the plane of the page, as shown below, then enters the region of magnetic field with a speed $v = 3.0 \times 10^5$ m/s. The magnitude of the field is 0.030 T. The effects of gravity are negligible.
[Diagram: a grid of "$\times$" symbols representing magnetic field B into the page. A proton (labeled "Proton") enters from the left moving to the right with velocity v into the field region. A separate coordinate-axis diagram alongside shows x (to the right), y (upward), and z (out of the page).]
Calculate the magnitude of the force on the proton as it enters the field.
(b)(ii) On the figure below, sketch a possible path of the proton as it travels through the magnetic field. Clearly label the path P1.
[Diagram: a grid of "$\times$" symbols (field into the page) with a proton entering from the left moving to the right, labeled "Proton", with velocity v arrow.]

Question 1

(b)(iii) A second proton now enters the magnetic field at the same point and from the same direction but at a greater speed than the first proton. On the figure above, draw the path of the second proton as it travels through the field. Clearly label the path P2.
(b)(iv) Next an electric field is applied in the same region as the magnetic field, such that there is no net force on the first proton as it enters the region. Calculate the magnitude and indicate the direction of the electric field relative to the coordinate system shown in part (b).

Solution 1

(a) Mark scheme

- At t_1 and t_2 the loop is still entering the field region (only part of the loop's area is inside the field), so the flux through the loop is changing at the same constant rate at both instants (loop moves at constant speed v into a uniform field B) — the induced current has equal, nonzero magnitude at t_1 and t_2, and flows in the same direction. By t_3 the loop is entirely inside the field, so the enclosed flux is no longer changing, and there is no current. Current flows only when the flux through the loop is changing — equivalently, only the loop side that is within the field (cutting field lines) has moving charge carriers experiencing an unbalanced magnetic force ($\vec{F} = q\vec{v} \times \vec{B}$) driving current around the loop; the other side is field-free. By Lenz's law (the induced current opposes the increasing into-the-page

Solution 1

flux) or by direct force analysis on the charge carriers in each segment, the induced current flows counter-clockwise. Once the loop is fully inside the field (at t_3), the net EMF around the loop is zero and no current flows. [Scoring: 1 pt equal nonzero same-direction current at t1,t2; 1 pt no current at t3; 1 pt current depends on changing flux/force on charges; 1 pt correct counter-clockwise direction with flux-opposing or force-on-charge-carrier explanation; 1 pt coherent on-topic paragraph structure.]

Solution 1

(b)(i)

Mark scheme

- $F = qvB = (1.6 \times 10^{-19}\ \mathsf{C})(3.0 \times 10^{5}\ \mathsf{m/s})(0.030\ \mathsf{T}) = 1.4 \times 10^{-15}\ \mathsf{N}$.

Solution 1

(b)(ii)

Mark scheme

- The proton follows a circular arc, curving upward (+y direction) from the entry point — consistent with the magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ on a positive charge moving in $+x$ through a field into the page ($-z$), which points in $+y$. Credit requires the arc to be no more than a semicircle and to reach (exit through) the edge of the field region; a path greater than a semicircle, or one that doesn't reach the field's edge, earns no credit.

Solution 1

(b)(iii)

Mark scheme

- Path P2 is a circular arc with a larger radius of curvature than P1 (from $r = mv/(qB)$: greater speed gives a larger radius for the same charge, mass, and field), curving in the same direction (upward) as P1, consistent with the P1 answer in (b)(ii).

Solution 1

(b)(iv)

Mark scheme

- For zero net force, the electric force must exactly cancel the magnetic force on the proton: $qE = qvB \Rightarrow E = vB = (3.0 \times 10^5 \text{ m/s})(0.030 \text{ T}) = 9000 \text{ N/C}$. Direction: the electric field must point opposite to the magnetic force direction used in (b)(ii) — since the magnetic force on the proton (moving in $+x$ through B into the page) points in $+y$ (consistent with the upward-curving path), the electric field must point in the $-y$ direction (toward the bottom of the page), so the electric force on the positive proton ($q\vec{E}$) points in $-y$ and cancels the magnetic force.

Question 4

2015 ▪ Q4

[Figure: A diagram showing an "Electron Source" (small filled square) at the top, above two horizontal parallel plates (shown as pairs of horizontal line segments with a gap between the left and right portions, indicating a hole at the center of each plate). The top plate and bottom plate are separated by distance d (marked with a vertical double-headed arrow on the left). An electron travels straight down through the hole in the top plate with velocity v_0 (arrow pointing down, at the top plate's central gap), continues down through the gap between the plates, and exits through the hole in the bottom plate with velocity v_f (arrow pointing down, at the bottom plate's central gap). Note: Figure not drawn to scale.]

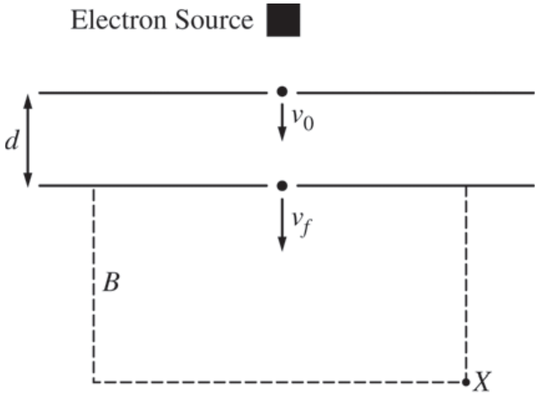
The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010$ m. Each plate has a hole at its center through which electrons can pass. High velocity

Question 4

electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6$ m/s, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6$ m/s.

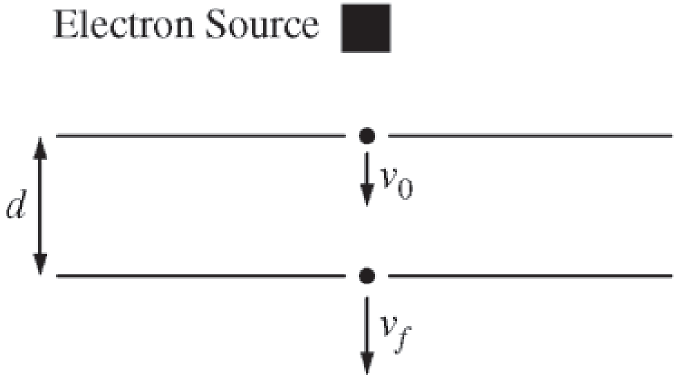
(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

Question 4



Note: Figure not drawn to scale.

Question 4



Note: Figure not drawn to scale.

Question 4

2015 ▪ Q4

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The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010$ m. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6$ m/s, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6$ m/s.

Question 4

(b) Calculate the magnitude of the electric field between the plates.

Question 4

2015 ▪ Q4

[Figure: A diagram showing an "Electron Source" (small filled square) at the top, above two horizontal parallel plates (shown as pairs of horizontal line segments with a gap between the left and right portions, indicating a hole at the center of each plate). The top plate and bottom plate are separated by distance d (marked with a vertical double-headed arrow on the left). An electron travels straight down through the hole in the top plate with velocity v_0 (arrow pointing down, at the top plate's central gap), continues down through the gap between the plates, and exits through the hole in the bottom plate with velocity v_f (arrow pointing down, at the bottom plate's central gap). Note: Figure not drawn to scale.]

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Question 4

(c) Calculate the magnitude of the charge on each plate.

Question 4

2015 ▪ Q4

[Figure: A diagram showing an "Electron Source" (small filled square) at the top, above two horizontal parallel plates (shown as pairs of horizontal line segments with a gap between the left and right portions, indicating a hole at the center of each plate). The top plate and bottom plate are separated by distance d (marked with a vertical double-headed arrow on the left). An electron travels straight down through the hole in the top plate with velocity v_0 (arrow pointing down, at the top plate's central gap), continues down through the gap between the plates, and exits through the hole in the bottom plate with velocity v_f (arrow pointing down, at the bottom plate's central gap). Note: Figure not drawn to scale.]

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Question 4

(d)(i) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude B that is perpendicular to the page. The electrons then leave the magnetic field at point X.
[Figure: Same electron-source/parallel-plate diagram as above (Electron Source square, top plate, electron traveling down at v_0, bottom plate, electron traveling down at v_f), but now below the bottom plate is a dashed-line box labeled B on its left edge, representing a region of uniform magnetic field perpendicular to the page. The bottom-right corner of the dashed box is labeled point X. Note: Figure not drawn to scale.]
On the figure above, sketch the path of the electrons from the bottom plate to point X. Explain why the path has the shape that you sketched.
(d)(ii) Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

Solution 4

(a) Mark scheme

- The top plate is negative. The electron speeds up as it travels from the top plate to the bottom plate ($v_f > v_0$: 8.02×10^6 m/s at exit vs. 5.40×10^6 m/s at entry), so the net electric force on it points downward, in its direction of motion. (1) Relate this force direction to the field direction: since the electron's charge is negative, the field must point opposite to the force on it, i.e. upward, from the bottom plate toward the top plate. (2) Relate the field direction to the plate charges: field lines point away from positive charge and toward negative charge, so a field pointing from the bottom plate toward the top plate means the bottom plate is positive and the top plate is negative. No credit for stating 'the top plate

Solution 4

is negative' without this two-step explanation (force-to-field, then field-to-charge-sign).

Solution 4

(b) Mark scheme

- Two equally-creditable 4-step derivations, both arriving at $E = 10{,}000$ N/C. KINEMATIC ROUTE: (1) find the electron's acceleration between the plates, $a = (v_f - v_i)/t$; (2) apply Newton's second law for the force needed, $F = ma = m(v_f - v_i)/t$; (3) set the electric force equal to this, $eE = F$; (4) solve for E and substitute: $E = \dfrac{m(v_f - v_i)}{et} = \dfrac{(9.11 \times 10^{-31}\ \text{kg})(8.02 \times 10^6 - 5.40 \times 10^6\ \text{m/s})}{(1.6 \times 10^{-19}\ \text{C})(1.49 \times 10^{-9}\ \text{s})} = 10{,}000$ N/C. ENERGY ROUTE: (1) apply conservation of energy, $\Delta K = \Delta U$; (2) use $\Delta U = e\Delta V$, giving $\frac{1}{2}m_e(v_f^2 - v_i^2) = e\Delta V$; (3) relate potential difference to field and plate separation,

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$\Delta V = Ed$, giving $\frac{1}{2}m_e(v_f^2 - v_i^2) = eEd$; (4) solve for E and substitute (plate separation d = 0.010 m): $E = \dfrac{m_e(v_f^2 - v_i^2)}{2ed} = \dfrac{(9.11 \times 10^{-31})[(8.02 \times 10^6)^2 - (5.40 \times 10^6)^2]}{2(1.6 \times 10^{-19}\ \text{C})(0.010\ \text{m})} = 10{,}000\ \text{N/C}$. Each of the four labeled steps in whichever route the student uses earns one point.

Solution 4

(c)

Mark scheme

- Use the parallel-plate relation $E = Q/(\varepsilon_0 A)$, rearranged to $Q = \varepsilon_0 AE$, and correctly substitute the known values (plate area $A = 0.25$ m^2, $E = 10{,}000$ N/C from part (b)):
$Q = (8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2})(0.25\ \mathrm{m^2})(10{,}000\ \mathrm{N/C}) = 2.2 \times 10^{-8}$ C. This is the magnitude of the charge on each plate.

Solution 4

(d)(i)

Mark scheme

- Draw a reasonably circular arc from the point where the electron leaves the bottom plate to point X (no penalty for exactly where the path starts relative to the arrow tip) (1 point). Explain that the magnetic force on a moving charge is always perpendicular to its velocity ($\vec{F} = q\vec{v} \times \vec{B}$), so as the electron moves, this force continuously acts perpendicular to the instantaneous velocity — a centripetal-type force that continuously turns the velocity direction without changing speed, producing a curved, circular path from the bottom plate to X (1 point).

Solution 4

(d)(ii) Mark scheme

- The magnetic field points out of the page. For the electron to reach point X, the magnetic field must exert a centripetal force on the electron directed toward the top-right corner of the dashed box (curving its path toward X). Using the right-hand rule for a positive charge moving with the electron's velocity would give a force in one rotational sense; since the electron is negatively charged, the actual force (and hence the field needed to produce it) is reversed from that positive-charge result (equivalently, apply the left-hand rule directly for the negative charge). Working through the rule with the electron's actual velocity and the required centripetal direction shows the field must point out of the page. No credit for stating the field direction without this explanation; credit can be earned

Solution 4

for a correct analysis at any individual point along the path, not just the entry point.