Past-paper walk-through

Electromagnetic Induction and Faraday's Law ▪ 12.4

eXercise

Questions in this set

- 2025 Q1
- 2022 Q4
- 2021 Q3
- 2018 Q1

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 1

2025 ▪ Q1

Very long Wire 1 carries current I in the $+x$-direction along the line $y = 0$. Very long Wire 2 carries current I in the $+x$-direction along the line $y = +d$. Point P is located along Wire 1 at the origin, as shown in Figure 1. The diameters of the wires are small compared to the distance between the wires. Both wires are in the xy-plane.
[Figure 1: Two horizontal wires drawn in the xy-plane, both carrying current I in the $+x$-direction (arrows point right, toward $+x$). Wire 2 lies along the line $y = +d$, above Wire 1, which lies along the line $y = 0$. Wire 1 passes through the origin, marked with a dot labeled P. A vertical y-axis passes through the point where Wire 1 crosses it, with the x-axis pointing right along Wire 1.]
Note: Figure not drawn to scale.
(a)(i) Complete the following tasks in figures 2 and 3. Use either arrows or the symbols shown in the box above the figures for your response.

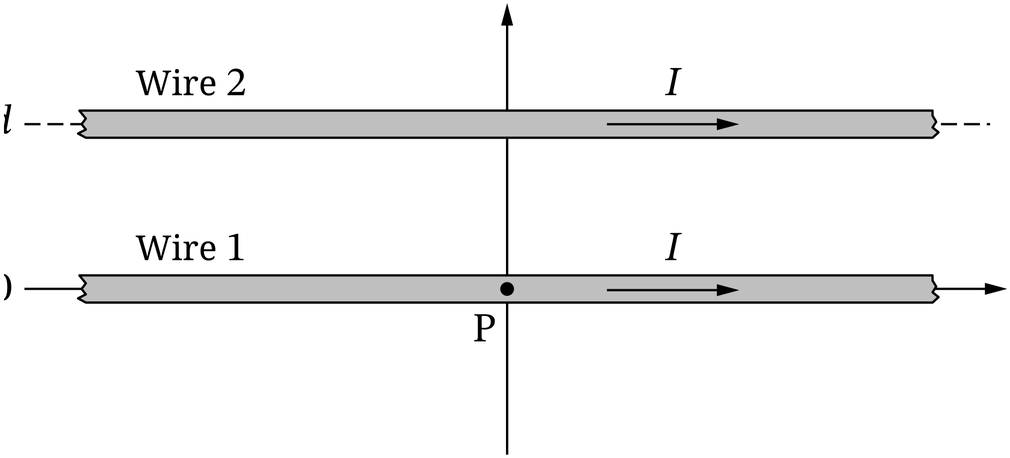
Question 1

Symbols: X = Into the page, = Out of the page

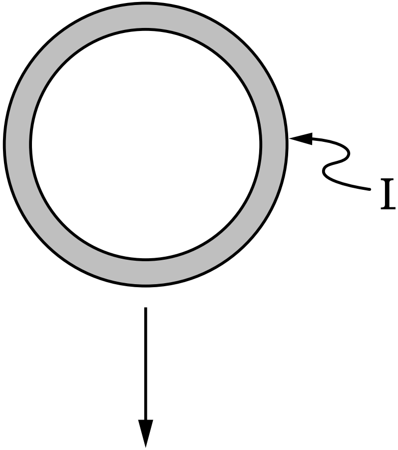
- **Indicate** the direction of the magnetic field from Wire 2 at Point P in Figure 2.
- **Indicate** the direction of the magnetic force that is exerted on Wire 1 by Wire 2 in Figure 3.

[Figure 2: an empty square box labeled "Magnetic Field from Wire 2 at Point P" for the student to draw the field direction.]
[Figure 3: an empty square box labeled "Magnetic Force on Wire 1 by Wire 2" for the student to draw the force direction.]
(a)(ii) Very long Wire 3 carrying current $2I$ in the $+x$-direction is placed in the xy-plane along the line $y = y_3$. The net magnetic force exerted on Wire 1 by the currents in wires 2 and 3 is zero.
Derive an expression for y_3 in terms of d. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 1



Question 1



Question 1

2025 ▪ Q1

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[Figure 1: Two horizontal wires drawn in the xy-plane, both carrying current I in the $+x$-direction (arrows point right, toward $+x$). Wire 2 lies along the line $y = +d$, above Wire 1, which lies along the line $y = 0$. Wire 1 passes through the origin, marked with a dot labeled P. A vertical y-axis passes through the point where Wire 1 crosses it, with the x-axis pointing right along Wire 1.]

Note: Figure not drawn to scale.

(b) Wire 3 is moved very far away from wires 1 and 2. A circular conducting loop in the xy-plane is initially held at rest below Wire 1. The loop is then moved at a constant speed in the $-y$-direction, as shown in Figure 4.

Question 1

[Figure 4: Wire 2 (carrying current I in the $+x$-direction) is above Wire 1 (also carrying current I in the $+x$-direction); a $+y$-axis arrow points upward on the right. Below Wire 1 is a circular conducting Loop, with an arrow below it pointing further in the $-y$-direction, showing the loop's direction of motion away from the wires.]

Note: Figure not drawn to scale.

Indicate whether there is a clockwise induced current in the loop, a counterclockwise induced current in the loop, or no induced current in the loop.

________ Clockwise

________ Counterclockwise

________ There is no induced current in the loop.

Justify your answer.

Solution 1

(a)(i)

Mark scheme

- The magnetic field from Wire 2 at Point P (Figure 2) is directed INTO the page (X symbol). The magnetic force exerted on Wire 1 by Wire 2 (Figure 3) is directed in the $+$y-direction (upward arrow) — since wires 1 and 2 carry parallel currents (both in $+$x), they attract, so Wire 1 is pulled toward Wire 2. (If a student instead indicates the field out of the page in Figure 2, full credit for the force requires it be shown in the -y-direction, i.e. consistent with an attractive force toward Wire 2.)

Solution 1

(a)(ii) Mark scheme

- Derive y3 using B = mu0*I/(2*pi*r) and Newton's second law (sum of forces = 0, since the net force on Wire 1 must be zero). Field from Wire 2 at Wire 1 (separation d): B2 = mu0*I/(2*pi*d). Field from Wire 3 at Wire 1 (current 2I, separation d3): B3 = mu0*(2I)/(2*pi*d3). Setting the magnitudes equal so the forces cancel (consistent direction requirement): mu0*I/(2*pi*d) = mu0*(2I)/(2*pi*d3), which gives d3 = 2d. Because Wire 3 must lie on the opposite side of Wire 1 from Wire 2 for its force to cancel Wire 2's force, y3 = -2d. Full credit requires: (1) a multistep derivation starting from B = mu0*I/(2*pi*r) and sum(F) = 0 or an equivalent relevant equation; (2) a correct expression for the field from Wire 2 along Wire 1, e.g. B2 = mu0*I/(2*pi*d); (3)

Solution 1

substituting 2I into an analogous expression for Wire 3 (field or force); (4) equating the magnitudes of the two fields/forces consistently; (5) the correct final expression $y3 = -2d$ (magnitude $|y3| = 2d$). A correct isolated final expression alone earns all remaining points.

Solution 1

(b) Mark scheme

- The induced current in the loop is clockwise. The magnetic field due to the currents in Wires 1 and 2 is directed into the page within the loop (both wires carry current in $+x$, and the loop is below them). As the loop moves in the -y-direction (away from the wires), the magnitude of the (into-the-page) magnetic flux through the loop decreases. By Lenz's law, the induced current opposes this decrease, so the induced current must produce its own magnetic field into the page inside the loop — by the right-hand rule this requires the induced current to flow clockwise (as viewed in the given orientation). Full credit requires: (1) stating the induced current is clockwise; (2) correctly identifying the field/flux from wires 1 and 2 as into the page within the loop; (3) correctly applying Lenz's

Solution 1

law to relate the decreasing |flux| to the direction of the induced field (into the page) produced by the induced current.

Question 4

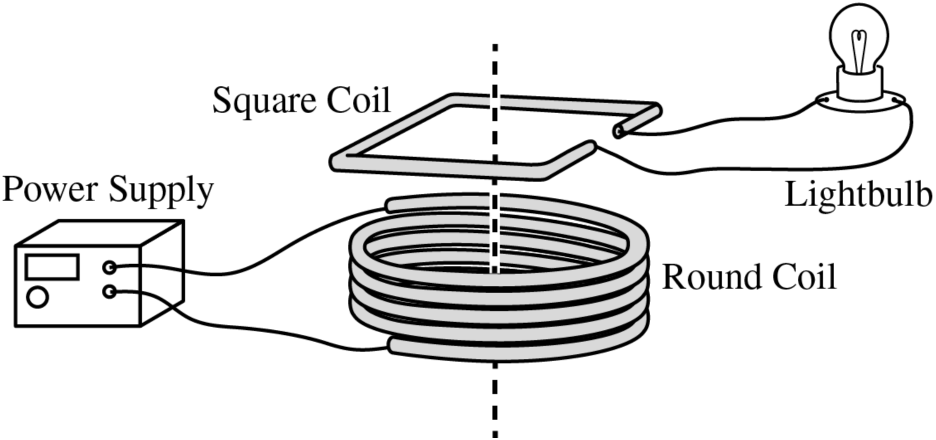
2022 ▪ Q4

[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.]

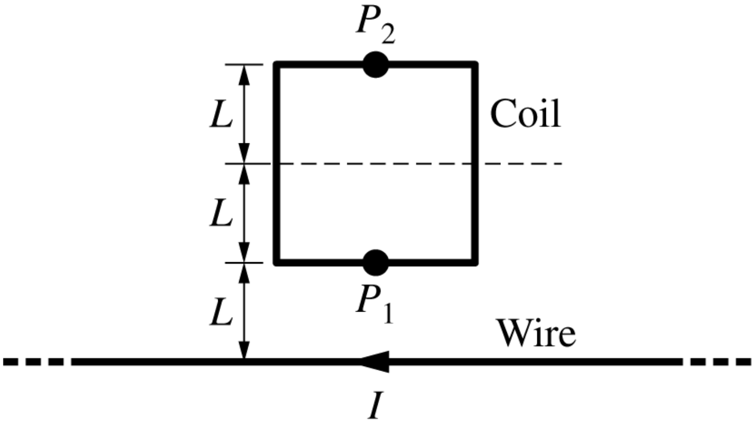
At the instant shown above, a negatively charged object is moving to the left with constant velocity v near a long, straight wire that has a current I directed to the left. The region contains a uniform electric field of magnitude E, and the charged object is at a distance d from the wire. The figure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

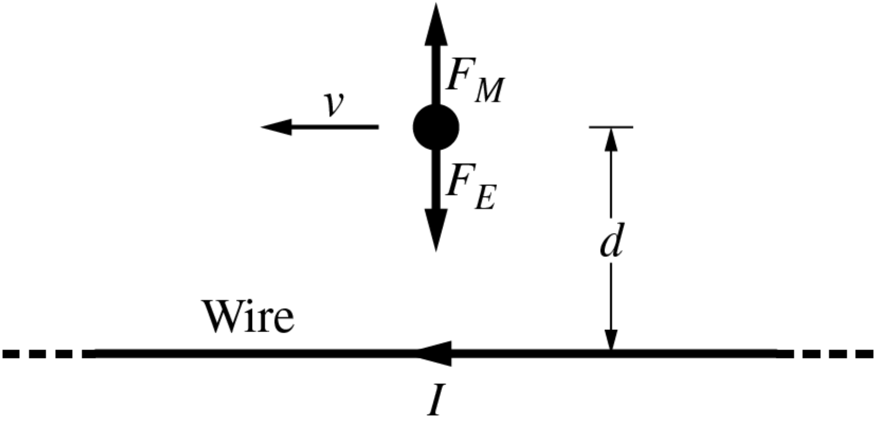
Question 4



Question 4



Question 4



Question 4

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.]

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(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

Question 4

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

Question 4

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.

Question 4

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.

(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

Question 4

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: $v\left(\dfrac{\mu_0 I}{2\pi d}\right) = E \Rightarrow v = \dfrac{2\pi dE}{\mu_0 I}$.

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 $2L$."

Solution 4

(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."

Question 3

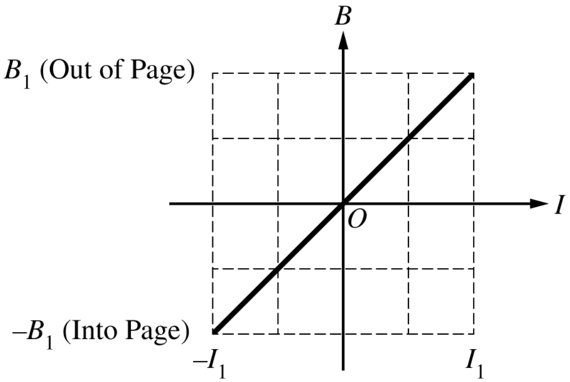
2021 ▪ Q3

[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".]
(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

Question 3

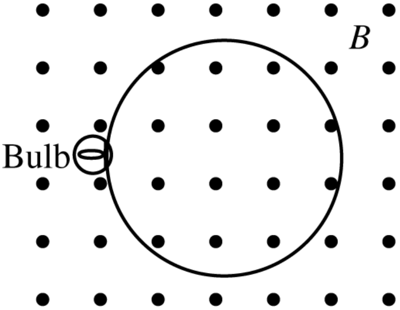
toward the left, as shown above. What changes to the current in the electromagnet could make the magnitude of the force exerted on the particle equal to $2F_B$ and the direction of the force to the right? Support your answer using physics principles.

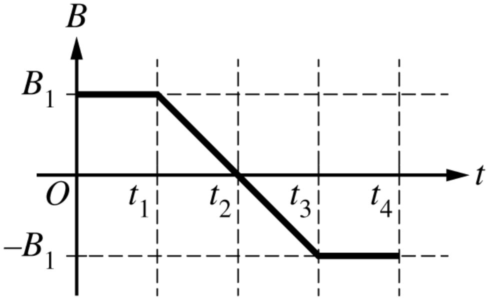
Question 3



Graph 1

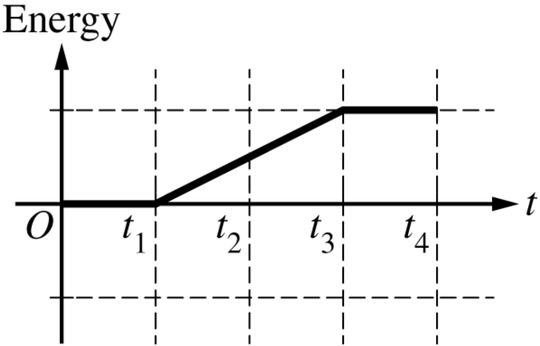
Question 3





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).]

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".]

(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).]

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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".]

(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, $P = \text{emf}^2/R$ (or $I = \text{emf}/R$, $P = I^2R$) 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

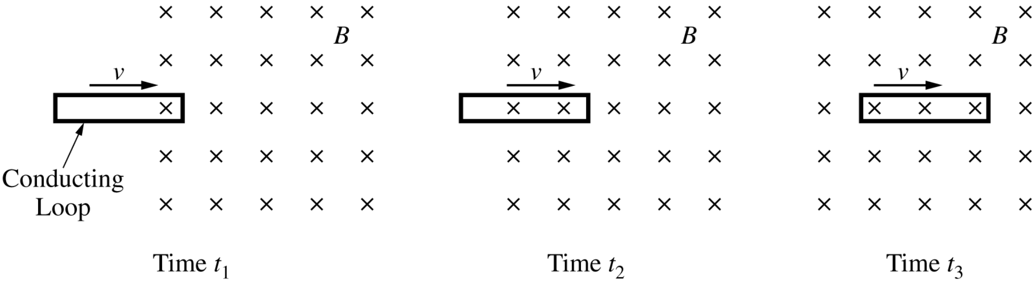
2018 ▪ Q1

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

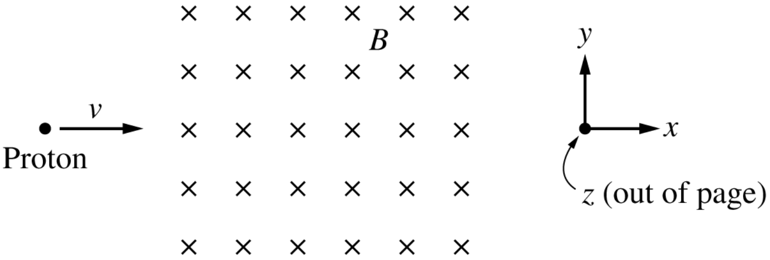
(a) In a coherent paragraph-length response, compare the magnitude and direction of the current at times t_1, t_2, and t_3. Include an explanation of why there is or is not a current and the direction of the current if one is present. Use fundamental physics concepts and principles in your explanation.

Question 1

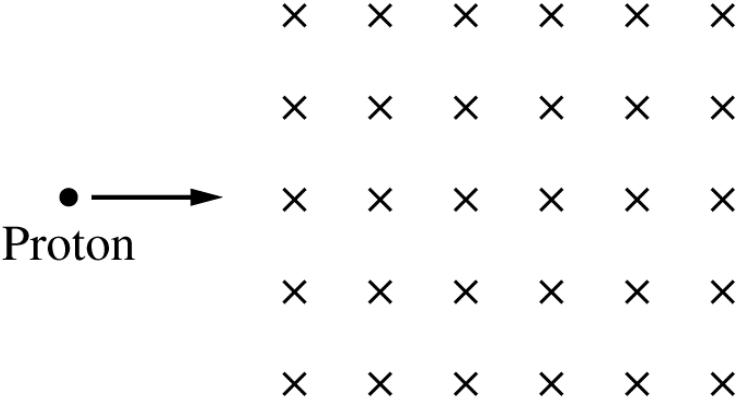


Question 1

of gravity are negligible.



Question 1



Question 1

2018 ▪ Q1

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

(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.