Past-paper walk-through

Magnetic Fields of Current-Carrying Wires and the Biot-Savart Law ▪ 12.3

eXercise

Questions in this set

- 2026 Q1
- 2025 Q4
- 2018 Q3

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

2026 ▪ Q1

Two very long, cylindrical, current-carrying Wires S and T are oriented parallel to the y-axis, as shown in Figure 1. The centers of the wires are in the xy-plane. The wires are described as follows.

- Wire S has radius $2a$ and is centered at $x = 0$. Wire S has nonuniform current density and carries total current I_0 in the $+y$-direction. The magnitude of the current density in Wire S as a function of the radial distance r from the center of the wire is described by $J = Cr$, where C is a positive constant.
- Wire T has radius a and is centered at $x = 10a$. Wire T has uniform current density and carries total current I_0 in the $-y$-direction.

Question 1

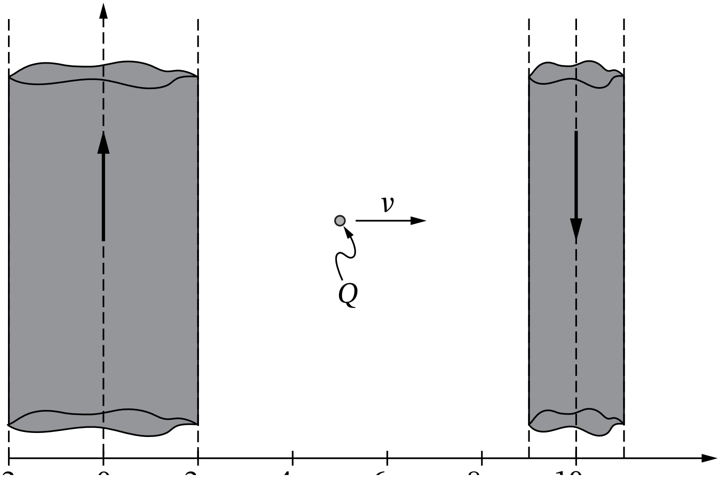
[Figure 1: Cross-section diagram in the xy-plane. Wire S is a shaded cylindrical bar centered at $x = 0$ spanning from $-2a$ to $2a$, with a y-axis arrow through its center pointing up (current I_0 in $+y$-direction) and a label $J = Cr$ pointing to the wire. Point P is marked inside Wire S, above the center axis, at horizontal position $x = a$. Wire T is a shaded cylindrical bar centered at $x = 10a$ spanning from $9a$ to $11a$, with a downward arrow through its center (current I_0 in $-y$-direction). The x-axis is marked with gridlines at $-2a, 0, 2a, 4a, 6a, 8a, 10a$.]

(a)(i) Point P is located inside of Wire S at horizontal position $x = a$. **Derive** an expression for the magnitude of the magnetic field at Point P due only to the current in Wire S in terms of C, a, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

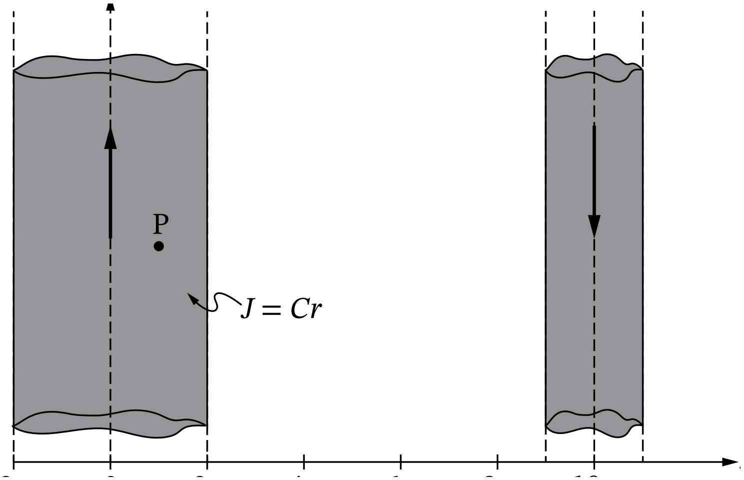
Question 1

(a)(ii) On the axes shown in Figure 2, **sketch** a graph of the magnitude B of the magnetic field due to the currents in both wires as a function of x along the x-axis in the region $2a \leq x \leq 9a$. Sketches made in the shaded region will not be graded. [Figure 2: A blank graph grid with vertical axis B and horizontal axis x, gridlines marked at $O, 2a, 3a, 4a, 5a, 6a, 7a, 8a, 9a$. The region from O to $2a$ is shaded (not to be used); the region from $2a$ to $9a$ is the graded sketch area.]

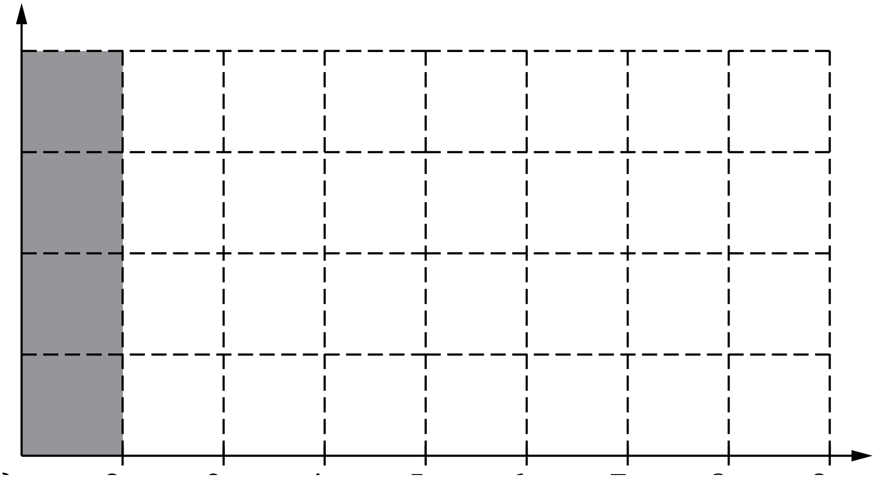
Question 1



Question 1



Question 1



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2026 ▪ Q1

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(b) At the instant shown in Figure 3, a small sphere with charge Q is at horizontal position $x = 5a$ and moving in the xy-plane with speed v in the $+x$-direction. At this instant, the net magnetic force exerted on the sphere due to the currents in Wires S and T has magnitude F.

[Figure 3: Same wire configuration as Figure 1 (Wire S centered at $x = 0$ with current I_0 in $+y$-direction, Wire T centered at $x = 10a$ with current I_0 in $-y$-direction). A

Question 1

small circle labeled Q is shown at $x = 5a$, midway between the wires, with an arrow labeled v pointing in the $+x$-direction.]
Derive an expression for F in terms of a, Q, I_0, v, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 4

2025 ▪ Q4

Long, parallel wires S and T are a distance $2d$ apart. Both wires carry equal currents I, but the currents are in opposite directions. Both wires are parallel to the x-axis. At the instant shown in Figure 1, Sphere 1 is a distance d above Wire S, Sphere 2 is a distance d below Wire S, and both spheres are moving with speed v in the $+x$-direction. Each sphere has positive charge $+Q$. Gravitational effects are negligible. [Figure 1: Sphere 1 is shown a distance d above Wire S, moving with velocity v in the $+x$-direction and carrying charge $+Q$. Wire S runs horizontally carrying current I to the right. A distance d below Wire S is Sphere 2, also moving with velocity v in the $+x$-direction and carrying charge $+Q$. A further distance d below Sphere 2 is Wire T, carrying current I to the left. A small 3D axis to the right shows $+y$ up, $+x$ to the right, and $+z$ out of the page (circle with a dot).]

Question 4

(a) F_1 is the magnitude of the magnetic force exerted on Sphere 1 due to the currents in wires S and T. F_2 is the magnitude of the magnetic force exerted on Sphere 2 due to the currents in wires S and T.

Indicate whether F_2 is greater than, less than, or equal to F_1 by writing one of the following.

- $F_2 > F_1$
- $F_2 < F_1$
- $F_2 = F_1$

Justify your answer.

Question 4

2025 ▪ Q4

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[Figure 1: Sphere 1 is shown a distance d above Wire S, moving with velocity v in the $+x$-direction and carrying charge $+Q$. Wire S runs horizontally carrying current I to the right. A distance d below Wire S is Sphere 2, also moving with velocity v in the $+x$-direction and carrying charge $+Q$. A further distance d below Sphere 2 is Wire T, carrying current I to the left. A small 3D axis to the right shows $+y$ up, $+x$ to the right, and $+z$ out of the page (circle with a dot).]

Question 4

(b) **Derive** an expression for the magnitude B_{tot} of the magnetic field at the location of Sphere 2 due to the currents in wires S and T in terms of d, I, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 4

2025 ▪ Q4

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Question 4

(c) Later, Wire T carries current $3I$ in the $+x$-direction. At the instant shown in Figure 2, Sphere 2 is a distance d below Wire S and is moving with speed v in the $+x$-direction. F_{new} is the new magnitude of the magnetic force exerted on Sphere 2 due to the currents in wires S and T.
[Figure 2: Wire S runs horizontally carrying current I to the right. A distance d below Wire S is Sphere 2, moving with velocity v in the $+x$-direction and carrying charge $+Q$. A further distance d below Sphere 2 is Wire T, now carrying current $3I$ to the right (same direction as Wire S). A small 3D axis to the right shows $+y$ up, $+x$ to the right, and $+z$ out of the page (circle with a dot).]
Indicate whether F_{new} is greater than, less than, or equal to F_2 by writing one of the following. - $F_{\text{new}} > F_2$ - $F_{\text{new}} < F_2$ - $F_{\text{new}} = F_2$
Briefly **justify** your answer by referencing your derivation in part B.

Solution 4

(a) Mark scheme

- F$_2 > F_1 . Themagneticforceonamovingchargehasmagnitude F =$
  $QvB, and Q and v are the same for both spheres, so the difference in force magnitudes comes entirely from$
  $F_1 . Points: (1) indicating F_2 >$
  $F_1, (2) correctly relating force magnitude to field magnitude (F \propto B, via F =$
  $QvB), (3) justifying that B is greater at Sphere 2's location than Sphere 1's, referencing relative distance$

Solution 4

(b) Mark scheme

- Start from Ampere's law $\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{enc} (ortheBiot - Savartlawd\vec{B} = \frac{\mu_0}{4\pi} \frac{I(d\vec{\ell} \times \hat{r})}{r^2}; vectornotationnotrequired).Forasinglelongstraightwire: B(2\pi d) = \mu_0 I, soB = \mu_0 I/(2\pi d) - -thefieldatSphere2duetoonewire.SincebothwiresSandTcarrycurrentIandtheirfieldsaddatSphere$ $B_{tot} = \frac{\mu_0 I}{2\pi d} + \frac{\mu_0 I}{2\pi d} = \frac{\mu_0 I}{\pi d}.Points: (1) multistepderivationincludingAmpere'sorBiot - Savartlaw(aderivationreachingB = \mu_0 I/(2\pi d) alsoearnsthis), (2) correctexpressionforthefieldatSphere2duetoonewire, (3) indicatingth$ $wirefield.$

Solution 4

(c) Mark scheme

- $F_{new} = F_2. Now Wire T carries 3I; the field at Sphere 2 due to Wire T is in the opposite direction to the field due to W$
  $\frac{3\mu_0 I}{2\pi d} - \frac{\mu_0 I}{2\pi d} = \frac{\mu_0 I}{\pi d} (OR : state directly that the net field magnitude at Sphere 2 stays the same even though the field from Wire T cha$
  $F_{new} = F_2. Points : (1) indicating F_{new} = F_2, (2) indicating B_{tot} = \frac{3\mu_0 I}{2\pi d} - \frac{\mu_0 I}{2\pi d} OR indicating that the net field magnitude at Sphere 2 remains the same even though the field from W$

Question 3

2018 ▪ Q3

[Figure 1. Side view: Wire 1 is shown end-on (circle with a dot, $\odot I_1$) with current I_1 directed out of the page; point P is a horizontal distance d from Wire 1. Wire 1 is a vertical distance d above Wire 2, which is drawn as a long horizontal wire (hatched double line) carrying current I_2 directed to the left.]
[Figure 2. Top view: Wire 1 is drawn as a vertical wire (with dashed extension above), Wire 2 is a horizontal wire to the left of Wire 1 carrying current I_2 directed to the left, and point P is a horizontal distance d to the right of Wire 1 along the same horizontal line as Wire 2's continuation. A note states: "Wire 1 and point P are a distance d above Wire 2." The current I_1 in Wire 1 is shown directed downward (out of the top-view plane arrangement).]
The figures above represent different views of two long, straight, horizontal wires, 1 and 2, carrying currents $I_1 = I$ and $I_2 = 2I$, respectively, in the directions shown. The

Question 3

wires are held in place. In Figure 1, the current in wire 1 is directed out of the page, and wire 1 is a distance d above wire 2. Point P is a horizontal distance d from wire 1 and a distance d directly above wire 2. Express your answers to parts (a) and (b) in terms of I, d, and physical constants, as appropriate.

(a) Use Ampere's law to derive an expression for the magnitude of the magnetic field at point P due to wire 1.

Question 3

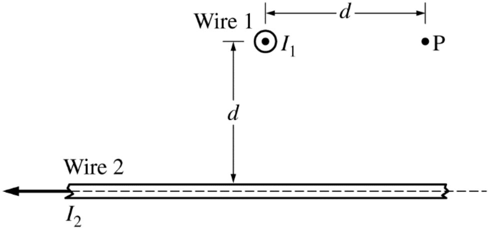

Figure 1. Side view

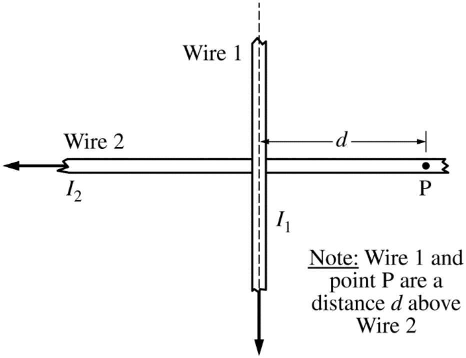

Figure 2. Top view

Question 3

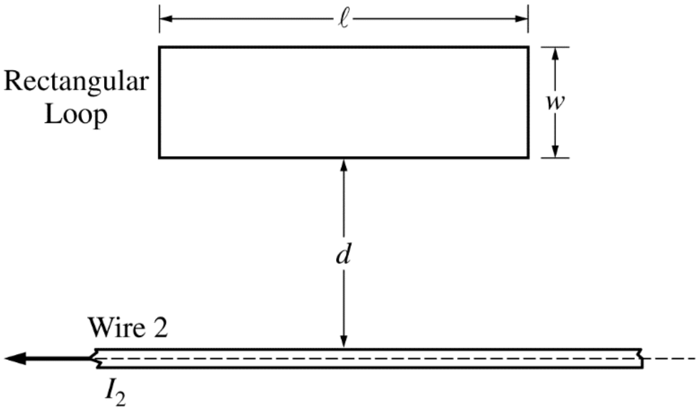

Figure 3. Side view

Question 3

2018 ▪ Q3

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Question 3

wire 2. Express your answers to parts (a) and (b) in terms of I, d, and physical constants, as appropriate.

(b) Derive an expression for the magnitude of the net magnetic field at point P.

Question 3

2018 ▪ Q3

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Question 3

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(c) Calculate the numerical value of the angle to the horizontal for the direction of the net magnetic field at point P.

Question 3

2018 ▪ Q3

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Question 3

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(d) Wire 1 is now released. Which of the following best describes the initial motion of wire 1 due to the magnetic field of wire 2? Assume gravitational effects are negligible.

_______ Wire 1 will not move.

_______ Wire 1 will move upward as viewed in Figure 1.

_______ Wire 1 will move downward as viewed in Figure 1.

_______ Wire 1 will rotate clockwise as viewed in Figure 2.

_______ Wire 1 will rotate counterclockwise as viewed in Figure 2.

Justify your answer.

[Figure 3. Side view: A rectangular loop of length ℓ (horizontal) and width w (vertical) is positioned above Wire 2, at a distance d from Wire 2 (measured from the bottom

Question 3

side of the loop down to the wire). Wire 2 (hatched double line) carries current I_2 directed to the left. The long side of the loop is parallel to the wire.]
Wire 1 is now replaced by a conducting rectangular loop of length ℓ, width w, and resistance R. The loop is placed a distance d from wire 2, as shown. The loop, wire, and distance d are all in the plane of the page. The long side of the loop is parallel to the wire. The current I_2 for wire 2 is decreasing linearly as a function of time t according to the equation $I_2 = 2I_0(1 - kt)$, where k is a positive constant with units of s^{-1}.

Question 3

2018 ▪ Q3

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Question 3

wire 2. Express your answers to parts (a) and (b) in terms of I, d, and physical constants, as appropriate.

(e) Of the following, select the integration that will give an expression for the flux Φ as a function of time t.

$$\Phi = \int_{r=d}^{r=d+w} \frac{\mu_0(2I_0)(1-kt)\ell w}{2\pi}\, dr$$

$$\Phi = \int_{r=d}^{r=w} \frac{\mu_0(2I_0)(1-kt)\ell w}{2\pi}\, dr$$

$$\Phi = \int_{r=d}^{r=d+w} \frac{\mu_0(2I_0)(1-kt)}{2\pi r}\, \ell\, dr$$

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Question 3

2018 ▪ Q3

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Question 3

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(f) Given that the flux through the rectangular loop as a function of time t is given by the equation

$$\Phi = \frac{\mu_0 I_0 \ell (1 - kt)}{\pi} \ln\left(\frac{d + w}{d}\right)$$

derive an expression for the magnitude of the current, if any, induced in the loop. Express your answers in terms of I_0, d, r, R, w, k, ℓ, and physical constants, as appropriate.

Question 3

2018 ▪ Q3

[Figure 1. Side view: Wire 1 is shown end-on (circle with a dot, $\odot I_1$) with current I_1 directed out of the page; point P is a horizontal distance d from Wire 1. Wire 1 is a vertical distance d above Wire 2, which is drawn as a long horizontal wire (hatched double line) carrying current I_2 directed to the left.]
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Question 3

wire 2. Express your answers to parts (a) and (b) in terms of I, d, and physical constants, as appropriate.

(g) What is the direction of the current, if any, induced in the loop as seen in Figure 3?
_______ Clockwise _______ Counterclockwise _______ Undefined, because there is no current induced in the loop
Justify your answer.

Solution 3

(a)

Mark scheme

- Apply Ampere's law around a circular loop of radius d centered on wire 1: $\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I \Rightarrow B(2\pi d) = \mu_0 I$ (1 point). Solve: $B = \dfrac{\mu_0 I}{2\pi d}$ (1 point).

Solution 3

(b) Mark scheme

- Field magnitudes at P: $B_1 = \dfrac{\mu_0 I}{2\pi d}$ from wire 1, and since $I_2 = 2I$, $B_2 = \dfrac{\mu_0 (2I)}{2\pi d} = \dfrac{\mu_0 I}{\pi d}$ from wire 2 (1 point, for indicating $B_2 = 2B_1$). Because B_1 and B_2 are perpendicular at P, the net field is their vector sum: $B_{net} = \sqrt{B_1^2 + B_2^2} = \sqrt{\left(\frac{\mu_0 I}{2\pi d}\right)^2 + \left(\frac{\mu_0 (2I)}{2\pi d}\right)^2} = \dfrac{\sqrt{5}\,\mu_0 I}{2\pi d}$ (1 point).

Solution 3

(c)

Mark scheme

- Relate the angle to the two perpendicular field components: $\theta = \tan^{-1}\left(\frac{B_1}{B_2}\right)$ (1 point). Substitute $B_1 = \mu_0 I/2\pi d$, $B_2 = \mu_0(2I)/2\pi d$: $\theta = \tan^{-1}(1/2) = 26.6^\circ$ (1 point).

Solution 3

(d)

Mark scheme

- Answer: Wire 1 will rotate clockwise as viewed in Figure 2. Justification: there is no net translational motion because the magnetic forces on the wire from wire 2's field cancel (1 point) — but there is a net torque causing rotation (1 point). Example: the top portion of wire 1 sits in a field into the page from wire 2 and feels a force to the right; the bottom portion sits in a field out of the page from wire 2 and feels a force to the left. The net force is zero, but the net torque is clockwise, so the wire rotates clockwise.

Solution 3

(e)

Mark scheme

- Correct choice: $\Phi = \int_{r=d}^{r=d+w} \frac{\mu_0(2I_0)(1-kt)}{2\pi r}\, \ell\, dr$ — the integrand is the field from wire 2 at distance r, $B(r) = \frac{\mu_0(2I_0)(1-kt)}{2\pi r}$, times the strip area element $\ell\, dr$, integrated over the loop's radial extent from $r = d$ to $r = d + w$.

Solution 3

(f) Mark scheme

- Take the time derivative of the given flux to get the EMF:
  $\varepsilon = \left|-\frac{d\Phi}{dt}\right| = \frac{\mu_0 I_0 \ell}{\pi} \ln\left(\frac{d+w}{d}\right) \left|\frac{d}{dt}(1-kt)\right| = \frac{\mu_0 I_0 k\ell}{\pi} \ln\left(\frac{d+w}{d}\right)$ (1 point).
  Divide by the loop's resistance R to get the induced current: $I = \frac{\varepsilon}{R}$ (1 point).
  Final answer: $I = \frac{\mu_0 I_0 k\ell}{\pi R} \ln\left(\frac{d+w}{d}\right)$ (1 point).

Solution 3

(g)

Mark scheme

- Answer: Clockwise, with a justification attempt (1 point). Reasoning: since I_2 is decreasing, the flux through the loop is decreasing (1 point). By Lenz's law, the induced current opposes this decrease, so it must create a magnetic field into the page inside the loop, meaning the induced current flows clockwise (1 point).