Theme D · Fields

Gravitational fields, electric and magnetic fields, motion of charges in electromagnetic fields, and — at HL — electromagnetic induction.

SUGGESTED TIME	TOTAL MARKS	QUESTIONS	MULTIPLE CHOICE
60 minutes	**52**	**10**	**6**

SECTION	**D · Fields**
IN THE FORMAT OF	Paper 1A (multiple choice), Paper 1B (data-based), and Paper 2 (short answer and extended response)
ROUTES	SL only — 6 questions, 37 marks. SL and HL — the whole paper, 10 questions, 52 marks. Every question is tagged in the left margin.
DEMAND	**Routine 2 · Demanding 7 · Discriminating 1**
	The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.
SYLLABUS POINTS	D.1 · D.2 · D.3 · D.4

INSTRUCTIONS

- Answer all questions in the spaces provided.
- Show your working. Method marks are awarded even where the final answer is wrong.
- Give your answers to a sensible number of significant figures, with a unit.
- The mark scheme for this paper follows the last question.

THE PAPER

Theme D · Fields

Answer all questions. 52 marks in 60 minutes.

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1 SL

MULTIPLE CHOICE · ROUTINE · D.1 **[1]**

A planet has twice the mass and twice the radius of the Earth. The gravitational field strength at the Earth's surface is g. What is the field strength at the surface of the planet?

A g/4

B g/2

C g

D 2g

Answer

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2 SL

MULTIPLE CHOICE · DEMANDING · D.2 **[1]**

Two identical conducting spheres carry charges of +6.0 nC and −2.0 nC. They are touched together and then separated to their original distance apart. How does the magnitude of the force between them change?

A It becomes zero.

B It is reduced to one third of its original value.

C It is reduced to one twelfth of its original value.

D It increases to twelve times its original value.

Answer

3
SL

MULTIPLE CHOICE · ROUTINE · D.3

[1]

A proton moves in a circular path of radius r in a uniform magnetic field of magnitude B, perpendicular to its velocity. If the speed of the proton is doubled, what is the new radius?

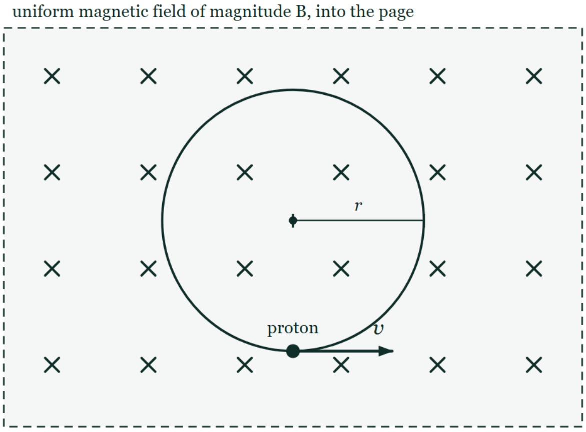

Figure 1 *A rectangular region bounded by a dashed line is filled with an evenly spaced grid of crosses and labelled 'uniform magnetic field of magnitude B, into the page'. Inside the region a complete circle is drawn: the path followed by the proton. A line from the centre of the circle out to the circle is marked with a tick at each end and labelled r. A solid dot on the circle at its lowest point is labelled 'proton', and from that dot an arrow labelled v points horizontally to the right, along the tangent to the circle.*

A r/2

B r

C 2r

D 4r

Answer

4 MULTIPLE CHOICE · DEMANDING · D.1 **[1]**

HL

A satellite of mass m is in a circular orbit of radius r around a planet of mass M. What is its total energy?

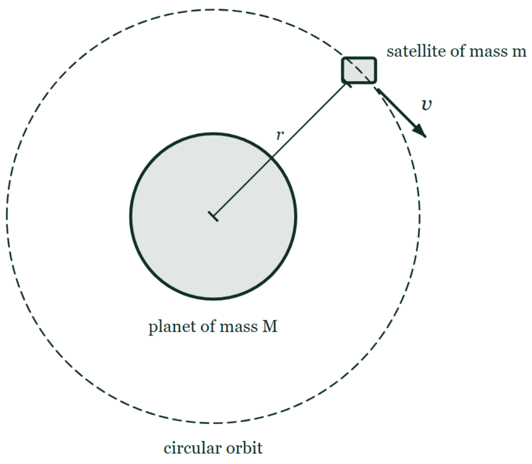

Figure 2 *A planet is drawn as a large shaded circle labelled 'planet of mass M'. A dashed circle, concentric with the planet and well outside it, is labelled 'circular orbit'. A small rectangle sitting on the dashed circle, above and to the right of the planet, is labelled 'satellite of mass m'. A short arrow from the satellite, drawn along the tangent to the orbit and labelled v, shows the direction in which it travels. A line runs from the centre of the planet out to the satellite and is labelled r.*

A $-GMm/(2r)$

B $-GMm/r$

C $+GMm/(2r)$

D zero

Answer

5 HL

MULTIPLE CHOICE · DEMANDING · D.4

[1]

A bar magnet is dropped, north pole downward, through a horizontal copper ring. Which describes the force on the magnet as it approaches the ring and after it has passed through?

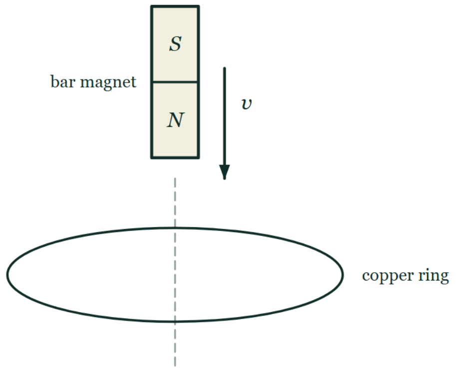

Figure 3 *Side view. A bar magnet is drawn vertically above a horizontal copper ring, with its two halves marked S at the top and N at the bottom, so that the north pole is the end facing the ring. An arrow beside the magnet, labelled v, points vertically downward. A faint dashed line continues from the bottom of the magnet straight down through the centre of the ring, which is drawn as a flattened ellipse to show it lying horizontally, and is labelled 'copper ring'.*

A upward as it approaches, upward after it has passed

B upward as it approaches, downward after it has passed

C downward as it approaches, upward after it has passed

D there is no force, because copper is not magnetic

Answer

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6 HL

MULTIPLE CHOICE · DEMANDING · D.2

[1]

Which statement about equipotential surfaces and field lines is correct for any static field?

A They are parallel to one another.

B They are perpendicular to one another.

C Work is done moving a charge along a field line but not along an equipotential.

D Both B and C are correct.

Answer

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7 DATA ANALYSIS · DEMANDING · D.2 **[10]**

SL

A student measures the magnetic flux density B at various perpendicular distances r from a long straight wire carrying a steady current I. Theory predicts $B = \mu_0 I/(2\pi r)$.

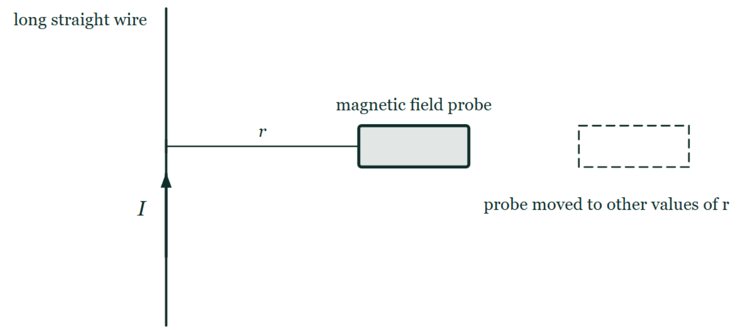

Figure 4 *A long straight wire is drawn vertically and labelled 'long straight wire'. An arrow drawn along the wire and labelled I gives the direction of the current in it. To the right of the wire, at the same height, a small rectangle labelled 'magnetic field probe' has its near face towards the wire, and a dimension line running perpendicular from the wire to that face is labelled r. A dashed outline of the probe, drawn further to the right at the same height, carries the note 'probe moved to other values of r'.*

The student's processed data

r / m	0.020	0.025	0.040	0.050	0.100
B / μT	50.0	40.0	25.0	20.0	10.0
1/r / m^{-1}	50.0	40.0	25.0	20.0	10.0

(a) EXPLAIN **[2]**

Explain why a graph of B against 1/r is plotted rather than a graph of B against r.

(b) DETERMINE **[4]**

Determine the gradient of the line, and hence determine the current in the wire.

(c) SUGGEST **[2]**

The student's measurements at the largest distances scatter more about the line than those close to the wire. Suggest why.

(d) OUTLINE **[2]**

Outline one systematic error that would make every value of B too large, and state how it would show up on the graph.

8

SL

STRUCTURED · DEMANDING · D.1 **[12]**

A planet has mass 6.4×10^{23} kg and radius 3.4×10^{6} m. The gravitational constant is 6.67×10^{-11} N m^{2} kg^{-2}.

(a) CALCULATE **[2]**

Calculate the gravitational field strength at the surface of the planet.

(b) DETERMINE **[3]**

Determine the escape speed from the surface of the planet.

(c) EXPLAIN **[3]**

Explain why gravitational potential is always negative, and state what a gravitational potential of -1.3×10^{7} J kg^{-1} at the planet's surface means.

(d) DISCUSS **[4]**

The planet has almost no atmosphere, while the Earth retains a substantial one. Discuss how the escape speed helps to explain this difference.

9 STRUCTURED · DEMANDING · D.2 · D.3 **[12]**

SL

An electron is accelerated from rest through a potential difference of 500 V and then enters a region of uniform magnetic field of magnitude 2.5 mT, travelling perpendicular to the field. The mass of an electron is 9.11×10^{-31} kg and its charge has magnitude 1.60×10^{-19} C.

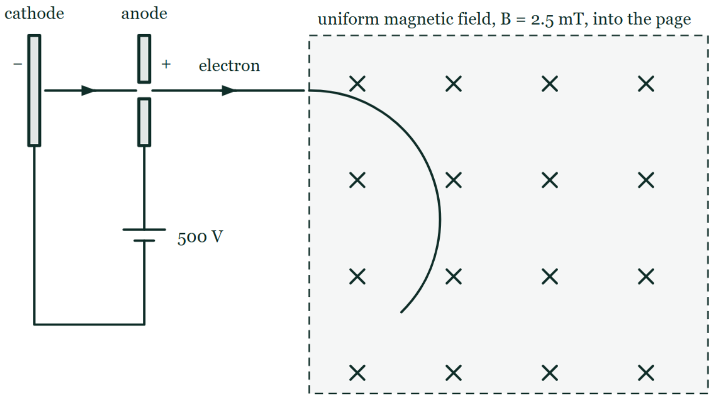

Figure 5 *Side view of the arrangement. At the left a cathode plate marked − faces an anode plate marked + which has a small hole in it at the level of the beam; below, the two plates are joined by wires through a cell labelled 500 V, whose positive terminal is connected to the anode. Arrows show an electron leaving the cathode, passing through the hole in the anode and travelling on to the right, where it crosses into a large rectangular region drawn with a dashed boundary and filled with crosses, labelled 'uniform magnetic field, B = 2.5 mT, into the page'. Inside that region the electron's path is drawn as an arc that curves steadily downwards away from its original straight line.*

(a) DETERMINE **[3]**

Determine the speed of the electron as it enters the magnetic field.

(b) DETERMINE **[3]**

Determine the radius of the circular path followed by the electron in the field.

(c) EXPLAIN **[3]**

Explain why the speed of the electron is unchanged while it moves within the magnetic field, even though its velocity is changing continuously.

(d) COMPARE **[3]**

A uniform electric field is now applied in the same region instead of the magnetic field, perpendicular to the electron's initial velocity. Compare the resulting path and the resulting speed with those in the magnetic field.

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10 HL

STRUCTURED · DISCRIMINATING · D.4 **[12]**

A flat rectangular coil of 250 turns and area 3.2×10^{-3} m² is rotated at a constant rate in a uniform magnetic field of magnitude 85 mT. The axis of rotation is perpendicular to the field. The coil completes 50 revolutions per second.

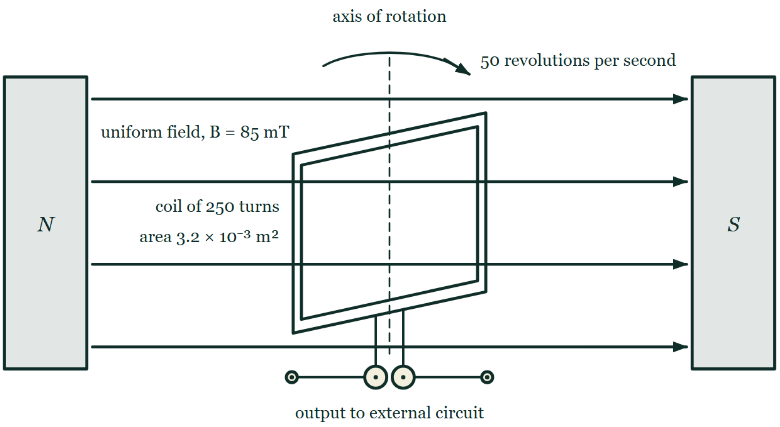

Figure 6 *A rectangular coil hangs between the flat faces of two poles, the north pole a block on the left and the south pole a block on the right. Four evenly spaced horizontal arrows run across the gap from the north pole to the south pole, and a note reads 'uniform field, B = 85 mT'. The coil is drawn obliquely, as a rectangle turned so that its plane lies at an angle to the field, and is labelled 'coil of 250 turns' and 'area 3.2 × 10⁻³ m²'. A vertical dashed line through the middle of the coil is labelled 'axis of rotation', with a curved arrow above it and the note '50 revolutions per second'. Two leads run down from the bottom of the coil to a pair of slip rings with brushes, whose terminals are labelled 'output to external circuit'.*

(a) STATE **[2]**

State Faraday's law of electromagnetic induction.

(b) DETERMINE **[3]**

Determine the maximum e.m.f. induced in the coil.

(c) EXPLAIN **[3]**

Explain why the induced e.m.f. is zero at the instant when the plane of the coil is perpendicular to the magnetic field, even though the flux through the coil is greatest at that moment.

(d) DISCUSS **[4]**

The output of the coil is connected to a resistor. Discuss the energy transfers taking place, and explain why more mechanical power must be supplied to keep the coil rotating at 50 revolutions per second once the resistor is connected.

MARK SCHEME

Theme D · Fields — mark scheme

One line per mark, as an examiner would award them. A note under a part is the error that part is set to catch.

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1 SL — MULTIPLE CHOICE · ROUTINE · D.1 — **[1]**

A planet has twice the mass and twice the radius of the Earth. The gravitational field strength at the Earth's surface is g. What is the field strength at the surface of the planet?

KEY **B** **g/2**

C is chosen by candidates who assume the two doublings cancel. In $g = GM/R^2$, the radius enters squared, so doubling both mass and radius gives 2/4 = ½.

A02

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2 SL — MULTIPLE CHOICE · DEMANDING · D.2 — **[1]**

Two identical conducting spheres carry charges of +6.0 nC and −2.0 nC. They are touched together and then separated to their original distance apart. How does the magnitude of the force between them change?

KEY **B** **It is reduced to one third of its original value.**

Touching shares the total charge of +4.0 nC equally, giving +2.0 nC on each, so the product of the charges falls from 12 nC^2 to 4 nC^2 and the force to one third. A is chosen by candidates who think the charges neutralise — they only partly do. The force also changes from attraction to repulsion, but the question asks about its magnitude.

A02

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3 SL — MULTIPLE CHOICE · ROUTINE · D.3 — **[1]**

A proton moves in a circular path of radius r in a uniform magnetic field of magnitude B, perpendicular to its velocity. If the speed of the proton is doubled, what is the new radius?

KEY **C** **2r**

B is the answer of a candidate who remembers that the period of circular motion in a magnetic field is independent of speed, which is true but is not what was asked. From $r = mv/(qB)$, the radius is proportional to the speed.

A02

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4 HL — MULTIPLE CHOICE · DEMANDING · D.1 — **[1]**

A satellite of mass m is in a circular orbit of radius r around a planet of mass M. What is its total energy?

KEY **A** **−GMm/(2r)**

B is the potential energy alone, forgetting that the satellite also has kinetic energy of +GMm/(2r). The total is negative, which is what makes the orbit bound.

A02

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5 HL — MULTIPLE CHOICE · DEMANDING · D.4 — **[1]**

A bar magnet is dropped, north pole downward, through a horizontal copper ring. Which describes the force on the magnet as it approaches the ring and after it has passed through?

KEY **A** **upward as it approaches, upward after it has passed**

B is the intuitive answer — the ring appears to repel then attract — but Lenz's law makes the induced effect oppose the motion in both stages. Approaching, the ring repels; receding, it attracts; and both act upward on a falling magnet. D confuses ferromagnetism with induction.

A02

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6 HL

MULTIPLE CHOICE · DEMANDING · D.2 **[1]**

Which statement about equipotential surfaces and field lines is correct for any static field?

KEY **D** **Both B and C are correct.**

Both statements are true and follow from the same fact: if a field had a component along an equipotential, moving a charge along it would do work and the potential would change. Candidates who stop at the first true statement they meet choose B or C.

AO2

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7 SL

DATA ANALYSIS · DEMANDING · D.2 **[10]**

A student measures the magnetic flux density B at various perpendicular distances r from a long straight wire carrying a steady current I. Theory predicts $B = \mu_0 I/(2\pi r)$.

(a) EXPLAIN · AO4 **[2]**

Explain why a graph of B against 1/r is plotted rather than a graph of B against r.

1. B is inversely proportional to r, so a graph of B against r is a curve from which no constant can be read
2. plotting against 1/r linearises the relationship, so the gradient gives $\mu_0 I/(2\pi)$ directly and the straightness of the line tests the inverse proportionality

(b) DETERMINE · AO2 **[4]**

Determine the gradient of the line, and hence determine the current in the wire.

1. gradient = $(50.0 - 10.0) \times 10^{-6} / (50.0 - 10.0) = 1.0 \times 10^{-6}$ T m
2. gradient = $\mu_0 I/(2\pi)$
3. $I = 2\pi \times 1.0 \times 10^{-6} / (4\pi \times 10^{-7})$
4. $I = 5.0$ A

(c) SUGGEST · AO3 **[2]**

The student's measurements at the largest distances scatter more about the line than those close to the wire. Suggest why.

1. the field is weakest at large r, so the reading is a smaller fraction of the probe's full scale and the percentage uncertainty in each reading is larger
2. the Earth's magnetic field and any stray fields are a larger fraction of the measured value at those distances

(d) OUTLINE · AO3 **[2]**

Outline one systematic error that would make every value of B too large, and state how it would show up on the graph.

1. the probe not being zeroed before the measurements, or the Earth's field component along the probe not being subtracted, would add a constant to every reading
2. the line would still be straight but would not pass through the origin — it would have a positive intercept on the B axis

The reasoning to reward is the link between the kind of error and its signature on the graph: a constant offset moves the intercept, a scale error changes the gradient.

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8 SL

STRUCTURED · DEMANDING · D.1 **[12]**

A planet has mass 6.4×10^{23} kg and radius 3.4×10^{6} m. The gravitational constant is 6.67×10^{-11} N m^{2} kg^{-2}.

(a) CALCULATE · AO2 **[2]**

Calculate the gravitational field strength at the surface of the planet.

1. $g = GM/R^2 = 6.67 \times 10^{-11} \times 6.4 \times 10^{23} / (3.4 \times 10^{6})^2$
2. $g = 3.7$ N kg^{-1}

(b) DETERMINE · AO2 **[3]**

Determine the escape speed from the surface of the planet.

1. escape requires the total energy to be zero: $\frac{1}{2}mv^2 = GMm/R$
2. $v = \sqrt{(2GM/R)} = \sqrt{(2 \times 6.67 \times 10^{-11} \times 6.4 \times 10^{23} / 3.4 \times 10^{6})}$
3. $v = 5.0 \times 10^{3}$ m s^{-1}

(c) EXPLAIN · AO2 **[3]**

Explain why gravitational potential is always negative, and state what a gravitational potential of -1.3×10^{7} J kg^{-1} at the planet's surface means.

1. gravitational potential is defined as zero at infinity, and gravity is always attractive
2. so bringing a mass in from infinity releases energy, and its potential energy must be less than zero everywhere else
3. the value means that 1.3×10^{7} J of energy must be supplied to move each kilogram from the surface to infinity

(d) DISCUSS · AO3 **[4]**

The planet has almost no atmosphere, while the Earth retains a substantial one. Discuss how the escape speed helps to explain this difference.

1. the molecules of a gas have a distribution of speeds, with some far above the mean at any temperature
2. molecules whose speed exceeds the escape speed at the top of the atmosphere can leave the planet permanently
3. this planet's escape speed of 5.0 km s^{-1} is less than half the Earth's 11.2 km s^{-1}, so a much larger fraction of its molecules exceed it
4. over geological time that fraction is lost, and the lightest gases go first — which is why any remaining atmosphere is thin and dominated by the heavier molecules

9 SL

STRUCTURED · DEMANDING · D.2 · D.3 **[12]**

An electron is accelerated from rest through a potential difference of 500 V and then enters a region of uniform magnetic field of magnitude 2.5 mT, travelling perpendicular to the field. The mass of an electron is 9.11×10^{-31} kg and its charge has magnitude 1.60×10^{-19} C.

(a) DETERMINE · AO2 **[3]**

Determine the speed of the electron as it enters the magnetic field.

1. $eV = \frac{1}{2}mv^2$
2. $v = \sqrt{(2 \times 1.60 \times 10^{-19} \times 500 / 9.11 \times 10^{-31})}$
3. $v = 1.33 \times 10^{7}\ \text{m s}^{-1}$

(b) DETERMINE · AO2 **[3]**

Determine the radius of the circular path followed by the electron in the field.

1. the magnetic force provides the centripetal force: $evB = mv^2/r$
2. $r = mv/(eB) = 9.11 \times 10^{-31} \times 1.33 \times 10^{7} / (1.60 \times 10^{-19} \times 2.5 \times 10^{-3})$
3. $r = 3.0 \times 10^{-2}$ m

(c) EXPLAIN · AO2 **[3]**

Explain why the speed of the electron is unchanged while it moves within the magnetic field, even though its velocity is changing continuously.

1. the magnetic force is always perpendicular to the velocity
2. so it has no component along the direction of motion and does no work on the electron
3. the kinetic energy is therefore constant, and only the direction of the velocity changes

(d) COMPARE · AO3 **[3]**

A uniform electric field is now applied in the same region instead of the magnetic field, perpendicular to the electron's initial velocity. Compare the resulting path and the resulting speed with those in the magnetic field.

1. in the electric field the force is constant in magnitude and direction, so the path is parabolic rather than circular
2. the force has a component along the velocity once the electron has been deflected, so it does work and the speed increases
3. in the magnetic field the force turns with the velocity, keeping the path circular and the speed constant

10 HL

STRUCTURED · DISCRIMINATING · D.4 **[12]**

A flat rectangular coil of 250 turns and area 3.2×10^{-3} m² is rotated at a constant rate in a uniform magnetic field of magnitude 85 mT. The axis of rotation is perpendicular to the field. The coil completes 50 revolutions per second.

(a) STATE · AO1 **[2]**

State Faraday's law of electromagnetic induction.

1. the magnitude of the induced e.m.f. is equal to the rate of change of magnetic flux linkage
2. expressed as $\varepsilon = -N\, d\Phi/dt$, the minus sign expressing Lenz's law

(b) DETERMINE · AO2 **[3]**

Determine the maximum e.m.f. induced in the coil.

1. $\omega = 2\pi f = 2\pi \times 50 = 314$ rad s^{-1}
2. $\varepsilon_0 = NBA\omega = 250 \times 0.085 \times 3.2 \times 10^{-3} \times 314$
3. $\varepsilon_0 = 21$ V

(c) EXPLAIN · AO3 **[3]**

Explain why the induced e.m.f. is zero at the instant when the plane of the coil is perpendicular to the magnetic field, even though the flux through the coil is greatest at that moment.

1. the induced e.m.f. depends on the rate of change of flux, not on the flux itself
2. when the plane of the coil is perpendicular to the field the flux is at a maximum, and at a maximum its rate of change is momentarily zero
3. so the e.m.f. is zero there and greatest a quarter of a cycle later, when the flux is passing through zero and changing fastest

The relationship between a quantity and its rate of change, tested on a case where intuition points the wrong way. This is one of the most reliably discriminating parts in the whole theme.

(d) DISCUSS · AO3 **[4]**

The output of the coil is connected to a resistor. Discuss the energy transfers taking place, and explain why more mechanical power must be supplied to keep the coil rotating at 50 revolutions per second once the resistor is connected.

1. with the circuit closed, the induced e.m.f. drives a current through the coil and the resistor, and electrical energy is dissipated in the resistor as thermal energy
2. the current-carrying coil sits in the magnetic field, so it experiences a torque
3. by Lenz's law that torque opposes the rotation of the coil
4. so an external agent must do work against it, and the mechanical power supplied equals the electrical power dissipated — energy is conserved, with the coil acting as the converter rather than the source

THE CHEAPEST MARKS ON ANY PAPER

What the command words are asking for

Every board publishes these and marks to them. A candidate who explains where the question said state has spent four minutes earning one mark; one who states where it said explain has earned none.

Define	Give the precise meaning of a word, phrase, concept or physical quantity.
State	Give a specific name, value or other brief answer without explanation or calculation.
Calculate	Obtain a numerical answer, showing the relevant stages in the working.
Describe	Give a detailed account.
Determine	Obtain the only possible answer, from the data or by reasoning.
Outline	Give a brief account or summary.
Compare	Give an account of the similarities between two or more items, referring to both throughout.
Discuss	Offer a considered and balanced review that includes a range of arguments, factors or hypotheses, supported by appropriate evidence.
Evaluate	Make an appraisal by weighing up the strengths and limitations.
Explain	Give a detailed account including reasons or causes.
Show (that)	Give the steps in a calculation or derivation.
Sketch	Represent by means of a graph showing a line and labelled but unscaled axes, with important features clearly identifiable.
Suggest	Propose a solution, hypothesis or other possible answer.

WHAT IS BEING TESTED

IB assessment objectives

Paper 1 has two parts: 1A is multiple choice, and 1B is data-based questions drawn from the experimental work of the course, with no recall in it at all. Paper 2 is short-answer and extended-response across the whole syllabus. HL papers are longer and reach the HL-only sub-topics. The data booklet is provided in every paper, so no question tests whether you can remember an equation.

AO1 2 MARKS · 4%	**Demonstrate knowledge** Recall facts, concepts and terminology, and state methodologies and techniques used in the course.
AO2 30 MARKS · 58%	**Understand and apply knowledge** Apply concepts, terminology and techniques to familiar and unfamiliar situations, including numerical work.
AO3 18 MARKS · 35%	**Analyse, evaluate and construct** Analyse and evaluate data, methods, claims and explanations, and construct a reasoned argument or conclusion.
AO4 2 MARKS · 4%	**Demonstrate the application of skills** Design and evaluate investigations, handle raw and processed data, treat uncertainties, and communicate results.