Index

The big picture (HL)

Higher level (HL)

? Guiding question(s)

- What are the effects of relative motion between a conductor and a magnetic field?
- How can the power output of electrical generators be increased?
- How did the discovery of electromagnetic induction affect industrialisation?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Figure 1 shows an induction hob. How does it heat the food in the pans?

Figure 1. An induction hob.

Credit: Tomazl, Getty Images

Induction hobs do not use direct heat like electric or gas hobs, but use rapidly changing magnetic fields to heat up the pans. The red glow is provided by light bulbs so that the user can see when the hob is switched on.

A constant current produces a constant magnetic field (see subtopic D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)). A current-carrying wire produces an unchanging magnetic field around it. In the 1830s, Michael Faraday tried to prove that the opposite was true – that a constant magnetic field could produce a current. He set up the circuit shown in **Figure 2**, but when the switch was closed, there was zero current in the second circuit.

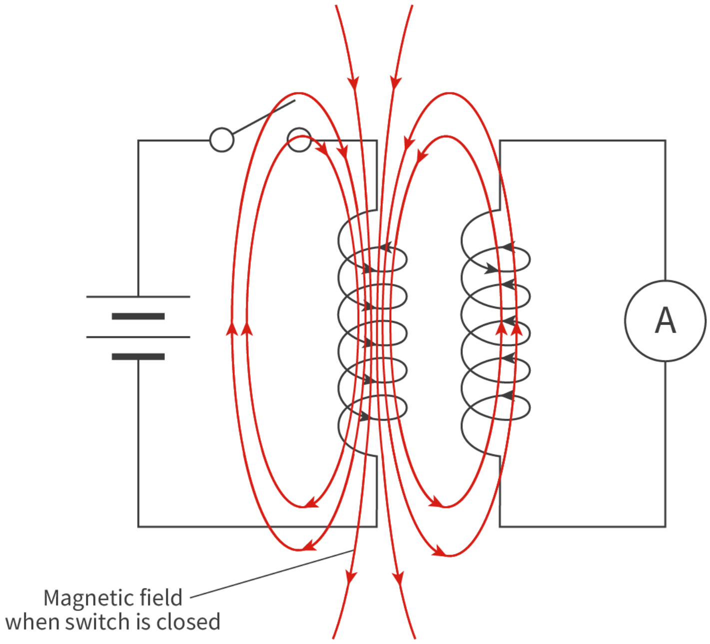

Figure 2. Faraday's circuit.

More information for figure 2

The diagram shows Faraday's circuit with two loops. On the left is a battery connected to a coil of wire. When the switch is closed, the magnetic field lines, illustrated in red, loop around the coil. The right side of the diagram has another coil connected to an ammeter, labeled 'A.' The magnetic field lines extend from the first coil to the second, illustrating the concept of electromagnetic induction. Text reads 'Magnetic field when switch is closed,' indicating the presence and direction of the magnetic field created.

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Faraday's experiment tried to prove that the constant magnetic field produced by the left-hand circuit would produce a constant electric current in the right-hand circuit. It failed, but with interesting results.

Faraday noticed that at the exact moment he turned the circuit on (closed the switch), a current flowed in the right-hand circuit. The same happened when he turned the circuit off (opened the switch). What was happening at these particular moments? How does this help us cook on an induction hob? And how did this discovery lay the foundations for our modern world?

Nature of Science

Aspect: Evidence

Science as a discipline works because of evidence. Scientists do not just think up a theory then tell other people about it. They must try to prove their theory with evidence, where possible. This evidence is used to inform, refine and sometimes disprove theories. Science is constantly evolving as new evidence is discovered, and theories need to be changed.

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Faraday's original theory was wrong, but he kept gathering evidence that enabled him to change his theory to describe reality better. Are there any theories that will always explain all the evidence? Have we 'completed' some areas of science?

Prior learning

Before you study this subtopic make sure that you understand the following:

- Current through a conductor produces a magnetic field around the conductor (see subtopic D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)).
- Electromotive force (emf) is the energy supplied to the charge carriers in a circuit, and this drives the charge carriers around the circuit (see subtopic B.5 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44361/)).
- Simple harmonic motion and circular motion are cyclical motions that result in predictable, repetitive movement, which can be described as sinusoidal (see subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)).

D. Fields / D.4 Induction (HL)

Describing magnetic fields (HL)

D.4.1: Magnetic flux (HL)

Higher level (HL)

Learning outcomes

At the end of this section you should be able to:

- Understand the terminology used when describing fields interacting with conducting wires.
- Identify the variables that can change the amount of magnetic flux penetrating a loop.
- Use the equation for magnetic flux: $\Phi = BA\cos\theta$

Experiment with Faraday's discovery in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-46422/) using the simulation in **Interactive 1**. First, select 'Voltmeter' to connect a voltmeter across the coil. Then think about the following questions:

- What happens when the magnet is not moving? Why? What happens when the magnet is moving?
- Can you identify the factors that affect the size of the electromotive force (emf) produced?

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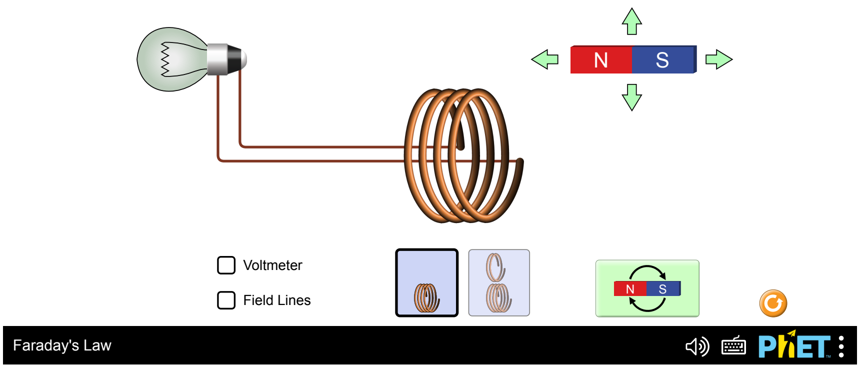

Interactive 1. Faraday's experiment.

More information for interactive 1

This interactive simulation explores **Faraday's Law of Electromagnetic Induction**, allowing users to investigate how a changing magnetic field induces an **electromotive force (emf)** in a coil. It provides an intuitive, hands-on way to understand the relationship between **magnetic flux, motion, and induced voltage**, reinforcing key principles of electromagnetism.

At the center of the simulation is a **bar magnet** that users can move through a coil of wire. When the magnet is stationary, the voltmeter shows zero, indicating no induced emf. However, as the magnet moves, the voltmeter displays a positive or negative voltage depending on the **direction of motion**. If the magnet is pushed into the coil, the voltage deflects in one direction. When the magnet is pulled away, the voltage deflects in the opposite direction, demonstrating how a changing magnetic field induces a current. Swapping the magnet's polarity also reverses the voltage readings, illustrating **Lenz's Law**, which states that the induced current opposes the change in magnetic flux.

Inside the coil, the **magnetic field lines dynamically adjust** as the magnet moves. Users can observe how the field interacts with the coil and affects the induced current. Additionally, if the simulation includes a **light bulb**, users will see it glow when a significant emf is generated, visually confirming the presence of an induced current. The brightness of the bulb depends on the strength of the induced emf, which increases with **faster magnet movement or a coil with more loops**.

The interactive also includes an option to use **two coils**, allowing users to explore mutual induction—how a changing magnetic field in one coil can induce a current in another nearby coil.

This simulation serves as a powerful educational tool for students, teachers, and anyone interested in understanding the fundamental principles of electromagnetism. By experimenting with different setups, users can gain insights into practical applications of Faraday's Law, such as electrical generators, transformers, and inductors, which are essential components of modern electrical systems.

Drag and drop the words in **Interactive 2** to explain what is happening in the simulation in **Interactive 1.**

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Drag the words into the correct boxes

From the simulation in Interactive 1, we can determine that the bulb lights up when the magnet is relative to the coil, and the bulb does not light up when the magnet is relative to the coil.

Decreasing the number of turns in the coil the brightness of the bulb.

Increasing the relative speed of the magnet the brightness of the bulb.

Reversing the direction of the magnet then moving it into the coil at a particular speed the brightness of the bulb.

decreases | increases | not moving | has no effect on | moving

Check

Interactive 2. Key Terms Related to Bulb Brightness.

Describing the field

Look at the simulation in **Interactive 1** again. Repeat the experiments, but this time select the 'Field lines' button. What do you notice about the pattern of the magnetic field lines? How does this affect the bulb?

Before we investigate moving magnetic fields, it is important to define some key terms to help us describe magnetic fields. We cannot see magnetic fields, so we have to find a way of representing them. As you can see from **Figure 2** in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-46422/) and the simulation in **Interactive 1**, we use lines. The properties of these lines represent certain features of the magnetic field (see subtopics D.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44096/) and D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)):

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-46422/print/) Assign

- The arrows on the magnetic field lines point in the direction that a force acts on a magnetic north pole in that location.
- The distance between the lines tells us the relative strength of the magnetic field. If the lines are close together, like the spaghetti in the left-hand picture in **Figure 1**, the field is strong. If the lines are further apart, like the right-hand picture, the field is weaker.

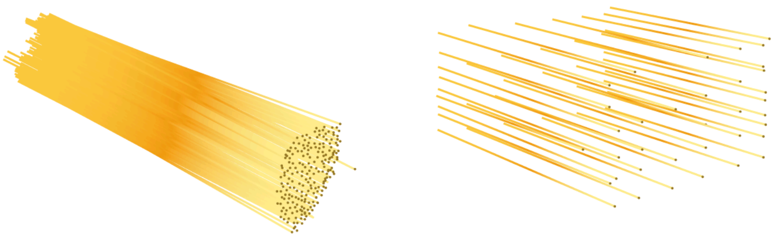

Figure 1. Spaghetti can be used to model magnetic field lines.

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Making connections

The definition of magnetic field strength, *B*, is given in subtopic D.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-45416/). It is derived from the force that the magnetic field exerts on a current-carrying conductor, such as a wire, at an angle, *θ*, to the magnetic field. The unit is the tesla (T), and the equation relating magnetic field strength to force is:

$$F = BIL\sin\theta$$

where F is force on the wire, L is length of the wire, and I is current flowing through the wire.

Magnetic flux

The amount of spaghetti in **Figure 1** is the same regardless of whether it is in the packet or is spaced out over a much larger volume. The total number of field lines is known as the magnetic flux, which has the symbol Φ. The unit of magnetic flux is webers (Wb).

Magnetic flux density, B, is how close together the field lines are, or how many field lines pass through a particular area. It is measured in webers per metre squared (Wb m^{-2}), or the equivalent unit tesla (T). The concentration of field lines is a representation of the magnetic field strength, and so:

$$\text{magnetic field strength} \equiv \text{magnetic flux density}$$

Theory of Knowledge

What is a unit? The scientific community has decided that we measure distance in metres, magnetic field strength in tesla and magnetic flux in webers. These are units that were invented by humans. Throughout the Universe, there is an equivalence between the density of magnetic field lines and the magnetic field strength, regardless of what units we use. To what extent are units meaningful? Do they only exist to help us communicate concepts, or does their meaning go deeper than this?

Figure 2 shows that for a certain area, A, there is a certain amount of magnetic flux, Φ. The magnetic flux per unit area is the magnetic flux density, which is equal to the magnetic field strength, B. The unit for magnetic flux density, Wb m^{-2}, is equivalent to the unit for magnetic field strength, T.

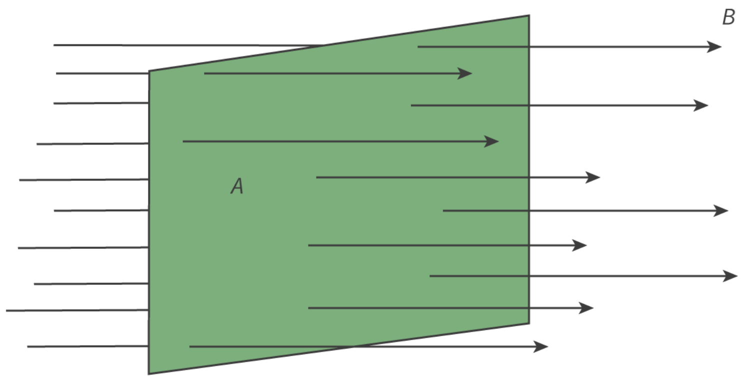

Figure 2. Magnetic field lines pass through an area, A.

More information for figure 2

The image is a diagram illustrating the concept of magnetic field lines passing through a defined area labeled 'A'. The green region represents the area in question. Multiple arrowed lines indicate the direction of the magnetic field, labeled as 'B', passing through this area. The arrows suggest a consistent direction of the magnetic field lines from left to right across the area 'A'. The density of lines does not vary, implying a

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uniform magnetic field strength through the area. This diagram visually supports the concept of magnetic flux and magnetic field strength (B) as discussed in accompanying text, highlighting the relationship between field, area, and magnetic flux density.

[Generated by AI]

Mathematically, this relationship can be written as:

$$\frac{\Phi}{A} = B$$

Rearranging gives:

$$\Phi = BA$$

In **Figure 2**, the magnetic field is shown as being normal to the area. If there is an angle θ between the magnetic flux and the normal (**Figure 3**), the equation for magnetic flux becomes the equation shown in **Table 1**.

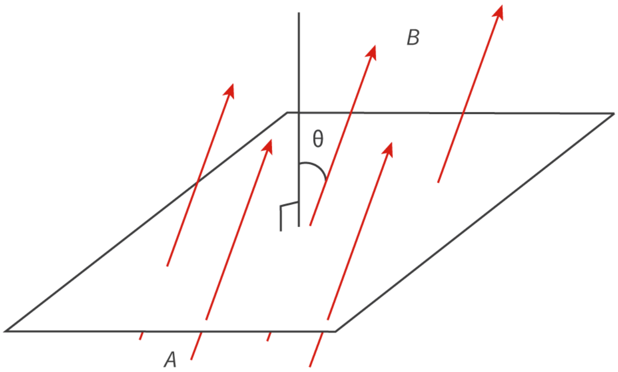

Figure 3. Magnetic field lines pass through an area, A, at an angle θ.

More information for figure 3

The diagram illustrates magnetic field lines passing through an area labeled 'A' at an angle represented by 'θ'. Several red arrows are drawn across the area, indicating the direction of the magnetic field, labeled 'B'. The field lines are shown at an angle 'θ' relative to a perpendicular line to the surface 'A'. This angle represents the deviation from being normal to the surface. The diagram helps visualize how magnetic flux changes with orientation according to angle 'θ'.

[Generated by AI]

Table 1. Equation for magnetic flux through a single plane.

Equation	Symbols	Units
$\Phi = BA\cos\theta$	\(Φ\) = magnetic flux	webers (Wb)
	B = magnetic field strength	tesla (T)
	A = area of space through which the magnetic flux is acting	metres squared (m^2)
	θ = angle between the lines of magnetic flux and the normal to the area, A	degrees (°)

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Study skills

Remember that θ in the equation in **Table 1** is the angle that the magnetic field makes to the **normal** to the area. If you are provided with the angle between the magnetic field and the area, you must use 90 − θ as the angle, or use sine instead of cosine.

Worked example 1

A conducting wire forms a circular loop with radius 35 cm, and the loop is moved into a magnetic field of strength 4.6 µT. The angle between the normal to the loop and the field is 32°. Determine the magnetic flux passing through the loop.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$B = 4.6\,\mu\text{T}$ $= 4.6\times10^{-6}\text{ T}$ $\theta = 32^\circ$ $r = 35\text{ cm}$ $= 0.35\text{ m}$ $A = \pi r^2$ $= \pi\times0.35^2$ $= 0.385\text{ m}^2$
Step 2: Write out the equation.	$\Phi = BA\cos\theta$
Step 3: Substitute the values given.	$= 4.6\times10^{-6}\times0.385\times\cos 32$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 1.5013\times10^{-6}\text{ Wb} = 1.5\times10^{-6}\text{ Wb}$

Remember to always convert units to SI units before executing calculations.

Worked example 2

When a circular loop of wire of radius 44 mm is in a magnetic field of strength 6.8 mT, the magnetic flux passing through the loop is 4.0 µWb.

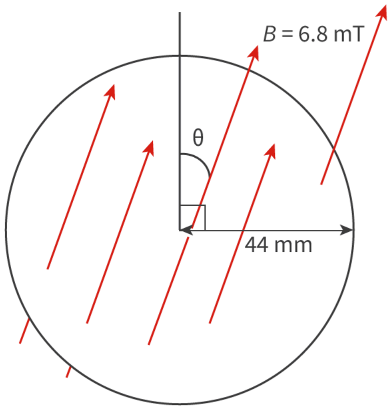

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Figure 4. A circular loop of wire in a magnetic field.

More information for figure 4

The image is a diagram depicting a circular loop of wire with a radius of 44 mm in a magnetic field. The magnetic field strength is indicated as 6.8 mT. Within the circle, several red arrows point diagonally upward from left to right, representing the direction of the magnetic field. An angle labeled θ is depicted between a vertical line and one of the magnetic field lines. A horizontal arrow indicates the radius of 44 mm from the center to the edge of the loop. This diagram illustrates the spatial relationship between the plane of the loop and the direction of the magnetic field lines, a key factor when determining the magnetic flux.

[Generated by AI]

Determine the angle between the plane of the loop and the magnetic field lines.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$r = 44 \text{ mm}$ $= 0.044 \text{ m}$ B = 6.8 mT = 6.8 × 10^{-3} T Φ = 4.0 μWb = 4.0 × 10^{-6} Wb A = πr^2 = π × 0.044^2 = 6.08 × 10^{-3} m^2
Step 2: Write out the equation and rearrange to find θ.	$\Phi = BA\cos\theta$ $\theta = \cos^{-1}\left(\frac{\Phi}{BA}\right)$
Step 3: Substitute the values given.	$= \cos^{-1}\left(\frac{4.0 \times 10^{-6}}{6.8 \times 10^{-3} \times 6.08 \times 10^{-3}}\right)$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 84.45°$ This is the angle between the field and the **normal to the loop**, so you need to calculate the angle between the **plane of the loop** and the field: $= 90–84.48 = 5.52° = 5.5° \text{ (2 s.f.)}$

Magnetic flux through a coil of wire

In the simulation in **Interactive 1**, you saw that the magnetic field lines were passing through a coil of wire, not just a single loop. You may have also noticed that the more turns the coil had, the brighter the bulb was (at the same magnet velocity).

Figure 5 shows two loops of wire, each with the same magnetic flux passing through. If these two loops were joined to make a coil with two turns, the coil would have twice the flux of a single loop. Similarly, a coil with three turns would have three times the flux of a single loop. Therefore increasing the number of turns in a coil of wire is a very effective way to increase the magnetic flux through the coil.

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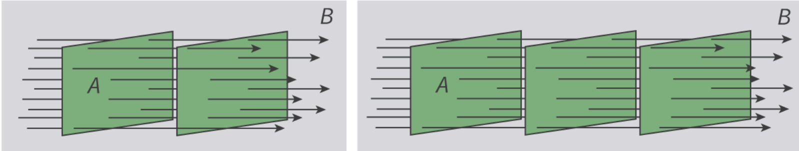

Figure 5. Magnetic field lines through loops of wire.

More information for figure 5

The image consists of two diagrams illustrating magnetic field lines passing through loops of wire. On the left side, there are two loops labeled 'A'. The magnetic field lines are depicted as straight horizontal arrows going from left to right, passing through the loops. The letter 'B' is shown to the right, indicating the magnetic flux. This section emphasizes the concept of magnetic flux through a single loop.

On the right side, the diagram is similar but with three loops labeled 'A', indicating a coil with more turns. The magnetic field lines, similarly depicted as horizontal arrows, pass through all three loops. Again, the letter 'B' is present on the right side, showing that increasing the number of turns in the coil increases the magnetic flux proportionally. The overall comparison shows that more loops result in more magnetic flux, in line with the explanatory text before and after the image.

[Generated by AI]

A magnetic field that results in a magnetic flux of Φ passing through a single loop of wire of a given area can also result in a magnetic flux of B when it passes through a coil of N turns with the same area. The total magnetic flux passing through a coil of N turns can therefore be described by:

$$\Phi = BAN\cos\theta$$

Have a go at the crossword in **Interactive 3** to help you remember the terminology used in this section.

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Across

6

2 An area of space where an object experiences a force. *(5)*

3 A wire forming multiple loops. *(4)*

5 A flat two-dimensional area which defines a surface. *(5)*

6 The unit of magnetic field strength. *(5)*

Down

1 An imaginary line at 90° to a plane. *(6)*

2 The total number of magnetic field lines passing through a given area. *(4)*

4 The unit of flux. *(5)*

Check Show solution Retry

Interactive 3. Terminology Crossword.

More information for interactive 3

An interactive crossword puzzle features a grid with both horizontal and vertical slots where users can type in the correct answers, related to magnetic fields and related concepts. The interactive crossword puzzle presents two distinct lists of clues adjacent to the crossword grid: Across and Down. There are 7 clues in total— 4 across and 3 down—each requiring the identification of a term that fits the given description. Each clue requires the identification of a term that fits the given description. The crossword grid consists of blank spaces where users can type

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in their answers, with real-time validation to ensure mistakes can be corrected. Below the grid are three interactive buttons: "Check," which allows users to verify their answers and confirms whether each one is correct or incorrect; "Show Solution," which reveals the correct answers for all clues, enabling users to compare their solutions; and "Retry," which resets the puzzle to allow a fresh attempt. Additionally, a progress bar at the bottom left corner tracks the number of correct answers, and once all answers are entered correctly, a 7/7 star rating appears to confirm completion.
Below is the full list of clues along with their respective clue number and the number of letters in the word at the end in brackets.

Across:

2. An area of space where an object experiences a force (5)

3. A wire forming multiple loops. (4)

5. A flat two-dimensional area which defines a surface. (5)

6. The unit of magnetic field strength. (5)

Down:

1. An imaginary line at 90° to a plane. (6)

2. The total number of magnetic field lines passing through a given area. (4)

4. The unit of flux. (5)

This interactive crossword puzzle serves as a valuable tool for reinforcing the user's understanding of terms related to magnetic fields and electromagnetic waves. By solving the crossword, users are encouraged to recall and apply concepts such as field strength, magnetic flux, and the variables that influence these properties.
Solutions

Across:

1. FIELD

2. COIL

3. PLANE

4. TESLA

Down:

1. NORMAL

2. FLUX

3. WEBER

Work through the activity to check your understanding of magnetic flux and magnetic flux density.

Activity

- **IB learner profile attribute:**
    - Communicator
    - Open-minded
- **Approaches to learning:** Communication skills — Reflecting on the needs of the audience when creating engaging presentations
- **Time required to complete activity:** 1 hour
- **Activity type:** Pair activity

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Visualising invisible lines of magnetic flux passing through an imaginary plane can be a difficult thing to do. Spaghetti was used to help you (**Figure 1**). This is an example of an analogy being used in science.

Build a model or devise an analogy that can help students visualise:

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- magnetic flux
- magnetic flux density
- multiple turns of a coil multiplying the magnetic flux passing through.

You could use household items, such as string, sticks or paper, or you could use a drawing app to create an image of your analogy. Be as creative and innovative as you can.

5 section questions

Question 1

HL Difficulty:

Magnetic 1 field strength ✓ is measured in 2 tesla ✓ and magnetic 3 flux density ✓ is measured in webers per metre squared. One 4 tesla ✓ is equivalent to one weber per metre squared.

Accepted answers and explanation

#1 field strength

#2 tesla
Tesla

#3 flux density

#4 tesla
Tesla

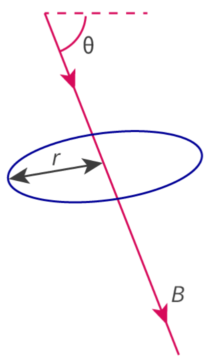
General explanation

Magnetic field strength is measured in tesla and magnetic flux density is measured in webers per metre squared. One tesla is equivalent to one weber per metre squared.

Question 2

HL Difficulty:

A magnetic field of strength B passes through a horizontal circle of radius r. The angle that the magnetic flux makes with the horizontal is θ.



More information

What is the equation for the magnetic flux passing through the circle?

1 $B\pi r^2 \sin\theta$ ✓

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2 $B\pi r^2$

3 $B\pi r^2 \cos\theta$

4 $B\pi r^2 \tan\theta$

Explanation

$\Phi = BA\cos\theta$

$A = \pi r^2$

The angle θ in the diagram is the complementary angle to the angle θ in the equation:

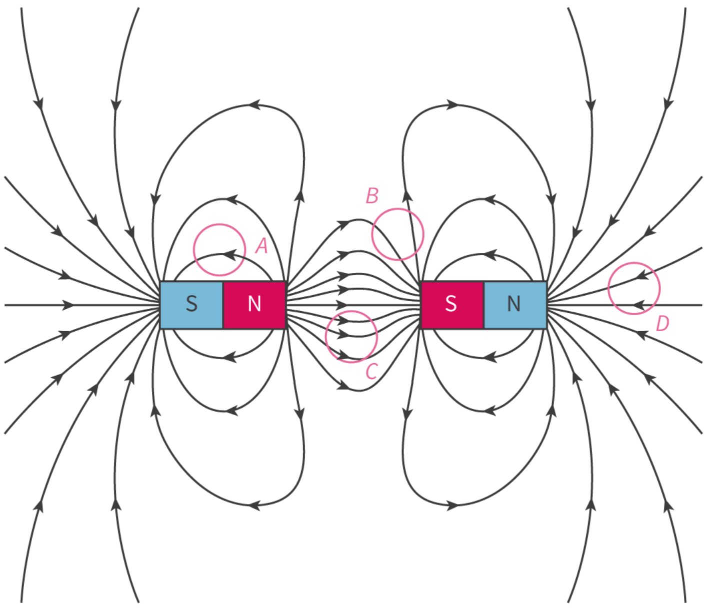
$$\theta_{\text{diagram}} + \theta_{\text{equation}} = 90^\circ$$

$$\begin{aligned}\Phi &= BA\cos(90 - \theta_{\text{diagram}}) \\ &= B\pi r^2 \sin\theta_{\text{diagram}}\end{aligned}$$

Question 3

HL Difficulty:

At which point (A, B, C or D) on the diagram is the magnetic field strength the greatest?



More information

1 C

2 A

3 B

4 D

Student view

Explanation

The magnetic field strength is greatest where the field lines are closest together, which is *at C*.

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Question 4

HL Difficulty:

The magnetic flux passing through a square loop of wire of side length 53.0 cm is given by:

$$\Phi = 9.27\times10^{-4}\sin 30.0$$

Which row in the table gives the correct values for the magnetic field strength and the angle between the normal to the plane of the loop and the field lines?

	Magnetic field strength	Angle
A	3.30 mT	30°
B	3.30 mT	60°
C	1.75 mT	30°
D	1.75 mT	60°

1 B ✓

2 A

3 C

4 D

Explanation

$$\Phi = BA\cos\theta$$

The equation in the question uses sin instead of cos.

$\cos\theta = \sin(90-\theta)$, so $\sin(30) = \cos(60)$, so the angle between the normal to the loop and the magnetic field lines is $60°$.

$$\Phi = 9.27\times10^{-4}\sin 30.0$$

So:

$$BA = 9.27\times10^{-4}$$

The area is the square of the side length of the square loop:

$$\begin{aligned} B &= \frac{9.27\times10^{-4}}{0.53^2} \\ &= 3.30\times10^{-3}\ \mathrm{T} \\ &= 3.30\ \mathrm{mT}\ (3\ \mathrm{s.f.}) \end{aligned}$$

Question 5

HL Difficulty:

A coil of wire has 3 turns and is placed so a magnetic field of strength B passes through it at 90°. The total magnetic flux for all three turns is X. What is the radius of the coil?

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1 $\sqrt{\frac{X}{3B\pi}}$ ✓

2 $\sqrt{\frac{3B\pi}{X}}$

3 $\frac{X}{3B\pi}$

4 $\frac{3B\pi}{X}$

Explanation

$$\Phi = BA\cos\theta$$

$\theta = 0$ as it is the angle between the normal to the plane of the coil and the magnetic field lines. The magnetic field lines are at $90°$ to the plane of the coil, so $\theta = 0$ and $\cos\theta = 1$.

$$A = \pi r^2$$

The magnetic flux, Φ, through one turn is:

$$\Phi = B\pi r^2$$

Three turns mean that each line of magnetic flux passes through a turn three times, so the total magnetic flux, X, is tripled for three turns:

$$X = 3B\pi r^2$$

$$r = \sqrt{\frac{X}{3B\pi}}$$

D. Fields / D.4 Induction (HL)

Inducing an emf (HL)

D.4.2: Faraday's law of induction (HL) D.4.3: Induction of an emf by a straight conductor moving perpendicularly to a uniform magnetic field (HL)

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Higher level (HL)

Learning outcomes

At the end of this section, you should be able to:

- Describe and explain the effect of a changing magnetic field on the emf in a conductor in that field.
- Calculate the induced emf in a conductor using $\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$ and $\varepsilon = BvL$.

Imagine a flashlight that could light up forever without ever needing new batteries. Is this science fiction? Not at all. These flashlights are called dynamo flashlights, and they work by generating an emf using a moving coil of wire and a magnet (**Figure 1**).

Almost all electricity that we use every day is generated in this same way – a moving coil and a magnet. How can something so simple power our whole society?

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Figure 1. Dynamo flashlight.

Effects of changing magnetic fields on electrons

When a magnetic field moves near a coil of wire, it induces a current in that wire. We can now refine that definition – a changing magnetic flux through a loop of wire or a coil induces a current in the loop or coil.

To understand this, we need to look at what is happening inside the wire. **Figure 2** shows an electron inside a conductor that is moving at a constant speed through a magnetic field. The direction of the magnetic field is into the page.

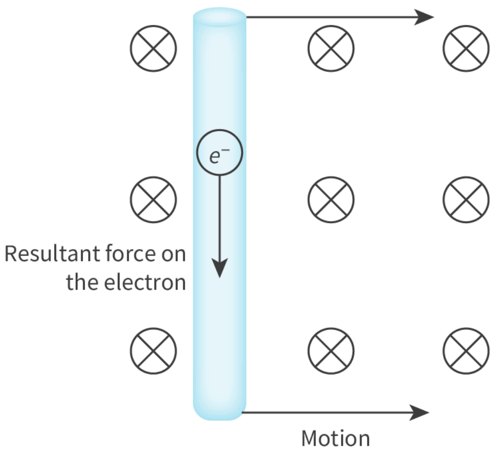

Figure 2. An electron inside a conductor moving at constant speed through a magnetic field.

More information for figure 2

The diagram illustrates a conductor with an electron inside, indicated by 'e-'. The conductor is vertical, and the electron is shown to be moving downward within it. The motion of the electron is represented by a downward arrow. Additionally, there is a horizontal arrow labeled 'Motion' pointing to the right, signifying the conductor's motion through the magnetic field. Outside the conductor, several circles with an 'X' inside them indicate the direction of the magnetic field, pointing into the page. The text 'Resultant force on the electron' is labeled alongside the electron, illustrating the force acting upon it due to the magnetic field.

[Generated by AI]

How can we work out what happens to the electron in **Figure 2**?

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When a charge carrier, such as an electron, moves a magnetic field is produced (subtopic D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)). If the conductor moves to the right, the electrons inside the conductor also move to the right. The electrons are moving, so this produces a magnetic field. This magnetic field interacts with the magnetic field going into the page, which exerts a force on the electrons.

Study skills

When drawing magnetic fields or current that are perpendicular to the plane of the page (or screen), we use a dot or a cross to show the direction. A cross means the field or current is directed into the page, while a dot means the field or current is directed out of the page. A circle drawn around the dot or cross can mean 'contained within a conductor', such as a wire, so this often (though not always) represents a current.

Figure 3. The convention for drawing magnetic fields or currents perpendicular to the plane of the page.

More information for figure 3

The image is a diagram that explains the convention for representing magnetic fields or currents perpendicular to the plane of a page. The diagram consists of two parts:

1. At the top, there is a circle with a cross inside, labeled "Into the page." This symbol indicates that the magnetic field or current is directed into the page.
2. Below that, there is a circle with a dot in its center, labeled "Out of the page." This symbol indicates that the magnetic field or current is directed out of the page.

These symbols are used to visually communicate the directionality of magnetic fields or currents in diagrams, with the cross symbolizing a direction going into the page and the dot symbolizing a direction coming out of the page. This version of the image is used to tell whether the field is entering or exiting the plane of representation.

[Generated by AI]

You can use the right-hand slap rule (introduced in section D.3.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/motion-of-a-charged-particle-in-a-uniform-2-id-45418/)) to deduce the direction of this force. Hold your right hand as shown in **Figure 4**. Your thumb should be at right angles to your fingers.

If your fingers point in the direction of the magnetic field, and your thumb points in the direction of the conventional current, then the direction of a slap with your palm is the direction of the outcome: the force.

Student view

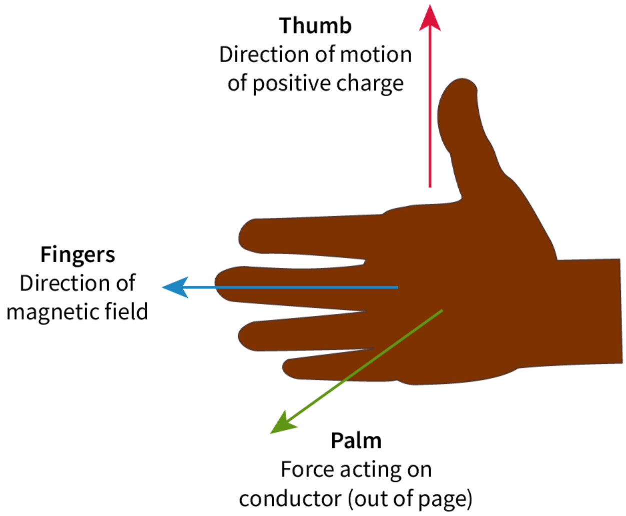

Figure 4. The right-hand slap rule showing the direction of the force on a current or moving charge in a magnetic field.

More information for figure 4

The image illustrates the right-hand slap rule used in physics to determine the direction of force on a moving charge in a magnetic field. It shows a right hand with fingers extended. The fingers point to the left, labeled as "Direction of magnetic field." The thumb points upward, labeled as "Direction of motion of positive charge." The palm faces outward, and an arrow extends from it, labeled "Force acting on conductor (out of page)." The arrows and labels illustrate the orientation needed to apply this rule.

[Generated by AI]

Nature of Science

Aspect: Models

Visualising three-dimensional situations can sometimes be difficult, especially when dealing with two-dimensional objects such as paper and screens. 3D models, such as the right-hand slap rule can help us visualise these situations more easily.

Using the right-hand slap rule, and remembering that conventional current flow is in the opposite direction to the movement of electrons, we can deduce that the force on the electron in **Figure 2** is to the left.

If the conducting wire in **Figure 2** is connected to a circuit, a current will flow in the 'upwards' direction for the section of wire shown (the opposite direction to electron flow). However it is important to remember that even if the wire is not connected to a circuit, the electrons still experience a force, producing a potential difference in the wire. There is a transfer of energy from kinetic energy to electrical potential energy. The amount of energy given to a coulomb of charge is the electromotive force, emf (subtopic B.5 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44361/)). Because this emf is produced by magnetic induction, we call it the induced emf.

Concept

Electromotive force (emf) is not a force. It is the **energy** supplied per unit charge in a circuit. This energy can be supplied by a chemical store (for example, a cell) or it can come from the mains supply, but it can also be induced — same concept, just produced in different ways. An induced emf can power a circuit in

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the same way as a battery.

There needs to be relative motion between the magnetic field and the wire to induce this emf (see section D.4.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-magnetic-fields-hl-id-46423/)). This is because of the principle of conservation of energy. The electrical energy must come from somewhere, so you need to input kinetic energy into the system.

You only induce an emf if you have a changing magnetic flux. The relationship between emf and rate of change of flux is known as Faraday's law, and it can be expressed using the equation in **Table 1**.

Table 1. Equation for induced emf.

Equation	Symbols	Units
$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$	ε = induced emf	volts (V)
	N = number of turns of the coil	unitless
	$\Delta\Phi$ = change in magnetic flux passing through the coil	webers (Wb)
	Δt = time taken for the change in magnetic flux to occur	seconds (s)

There are several different ways to induce this emf, but all of them lead back to the equation in **Table 1**. To make this easier to understand, we can arrange the equation in different ways, remembering that $\Phi = BA\cos\theta$.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Research skills — Comparing, contrasting and validating information
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

To induce an emf, we need to create a change in the magnetic flux passing through an area. Work out as many different ways to change this magnetic flux and induce an emf as you can. Then see if you can find any examples of your methods in the real world.

If you have access to school equipment, you could use:

- strong magnet
- coil of wire
- galvanometer or sensitive voltmeter.

If you do not have access to this equipment, look at the simulation in **Interactive 1** in section D.4.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-magnetic-fields-hl-id-46423/) or this falling magnet simulation (https://iwant2study.org/lookangejss/05electricitynmagnetism_22electromagneticinduction/ejss_model_Fallinc

Look at **Video 1** below if you need help.

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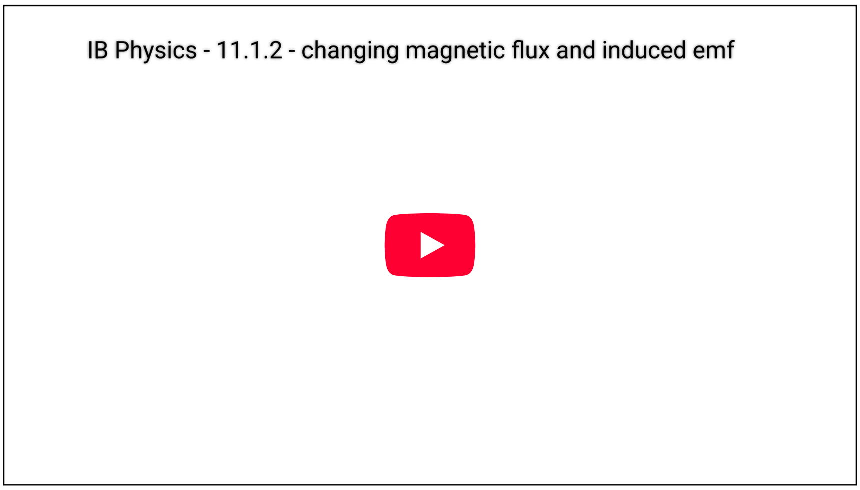
Inducing an emf

There are several ways to change the magnetic flux passing through a coil and induce an emf. **Video 1** shows three of them.

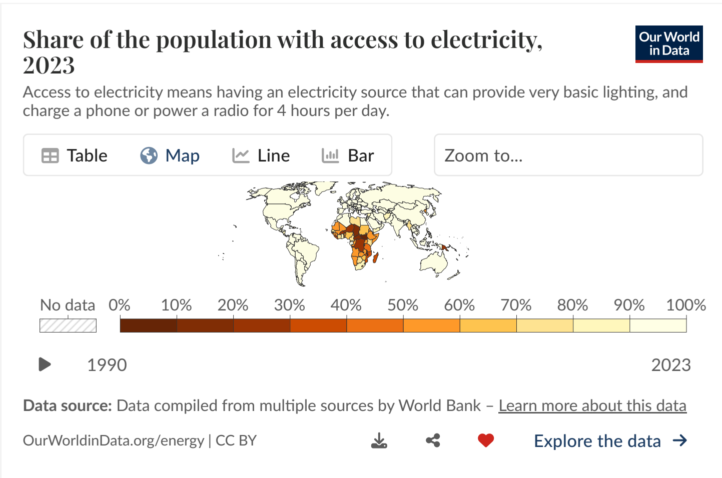


Video 1. Changing magnetic flux and induced emf.

Creativity, activity, service

Strand: Activity
Learning outcome: Demonstrate engagement with issues of global significance

Video 1 shows you how easy it is to generate an emf. But over 700 million people around the world do not have access to electricity. **Interactive 1** shows a map of where this is an issue.



Interactive 1. Access to electricity.

More information for interactive 1

This interactive visualization allows users to explore global progress in electricity access from 1990 to 2022, providing a dynamic way to track how different countries have expanded electrification over time. By engaging with the interactive, users can uncover key trends, regional disparities, and the factors influencing access to electricity worldwide.

The visualization is structured into three interactive sections: **Map, Chart, and Table**, each offering unique insights.

The map displays a geographical breakdown of electricity access by country. The color-coded system ranges from dark red (representing low or no access) to light yellow (indicating high access, close to or at 100%). The data reflects how electricity access has evolved across various regions, with certain parts of the world, particularly in sub-Saharan Africa, still facing significant challenges in providing electricity to the population. Over time, many regions show a shift towards increased access, with some countries showing rapid progress, while others, particularly in rural areas, lag behind.

The chart allows for a visual comparison over time, providing a clear view of the global trends in electricity access from 1990 to 2022. Users can see how certain countries or regions have improved their electricity infrastructure and how the

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global share of the population with access to electricity has increased significantly over the years. The chart makes it easy to spot trends, such as rapid electrification in parts of Asia, compared to slower progress in certain parts of Africa.
The Table provides detailed numerical data, allowing users to examine country-specific electricity access rates over time. This section is particularly useful for identifying outliers—countries that have made exceptional progress or continue to struggle with electrification.
By exploring these different perspectives, users can gain a deeper understanding of how electricity access has evolved globally, what factors contribute to successful electrification, and which regions still require significant efforts to achieve universal energy access. This interactive serves as a valuable tool for researchers, policymakers, and anyone interested in tracking global development and energy equity.

Notice the text: 'The definition used in international statistics adopts a very low cut-off for what it means to "have access to electricity". It is defined as having an electricity source that can provide very basic lighting, and charge a phone or power a radio for 4 hours per day.'

What challenges might be affecting access to electricity for these communities? What do you think the consequences are for these communities? How do you think you could raise awareness of this in your own community?

Moving magnet or coil

The simplest way to induce an emf is to have a magnet and a coil moving relative to each other, as in **Figure 5**. The magnetic field strength, B, in the area made by the coil changes as the magnet moves, so the emf is given by:

$$\varepsilon = -N\frac{\Delta BA}{\Delta t}$$

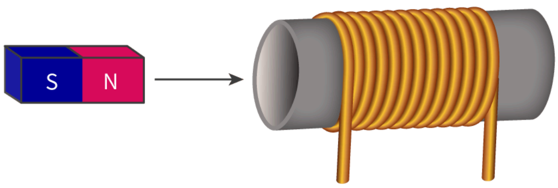

Figure 5. A magnet moving relative to a coil of wire generates an emf.

More information for figure 5

The image is an illustration showing a magnet and a coil of wire. The magnet is depicted as a rectangular block with clearly marked north (N) and south (S) poles. The coil is made of wire wrapped around a cylindrical core. An arrow is drawn between the magnet and the coil, indicating motion or interaction between them. This setup visually represents the concept of electromagnetic induction, where moving the magnet relative to the coil generates an electromotive force (emf). No specific color details or additional symbols are essential for understanding the concept in the illustration.

[Generated by AI]

This is the same as moving a coil into a stationary magnetic field as shown in **Figure 6**. The magnetic flux through the coil changes as the coil moves.

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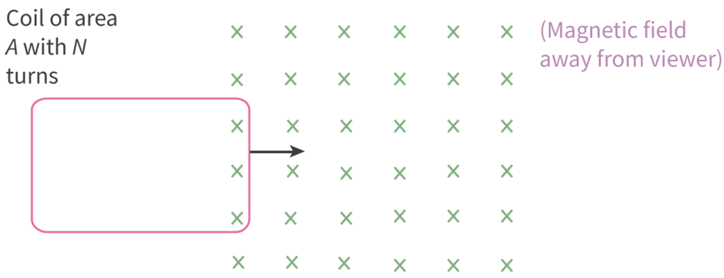

Figure 6. A coil moving into a stationary magnetic field results in a change in magnetic flux and an induced emf.

More information for figure 6

The diagram illustrates a coil moving into a stationary magnetic field represented by a grid of green Xs. The magnetic field is labeled as "Magnetic field away from viewer" on the right side of the diagram. On the left, the coil is depicted as a rectangle with the text "Coil of area A with N turns" next to it. An arrow points right from the coil into the magnetic field, indicating the direction of movement. The green Xs signify the magnetic field's direction, moving away from the viewer. This visual illustrates the change in magnetic flux as the coil moves into the field.

[Generated by AI]

Worked example 1

A circular coil with 130 turns and radius 65 mm is initially in an area with no magnetic field. It moves into a magnetic field of 5.5 μT in 0.34 ms. Calculate the induced emf.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$N = 130$ $r = 65\text{ mm}$ $= 65\times10^{-3}\text{ m}$ $B_1 = 0\,\mu\text{T}$ $B_2 = 5.5\,\mu\text{T}$ $= 5.5\times10^{-6}\text{ T}$ $\Delta t = 0.34\text{ ms}$ $= 0.34\times10^{-3}\text{ s}$ $A = \pi r^2$ $= \pi\times(65\times10^{-3})^2$ $= 0.01327\text{ m}^2$
Step 2: Write out the equation.	$\varepsilon = -N\dfrac{\Delta BA}{\Delta t}$
Step 3: Substitute the values given.	$= -130\times\dfrac{5.5\times10^{-6}\times0.01327}{0.34\times10^{-3}}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$= 0.0279\text{ V} = 0.028\text{ V (2 s.f.)}$

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Changing area

Another way the magnetic flux can change is if the area of the loop changes. Imagine a conducting rod rolling along two contacts in a constant magnetic field, completing a circuit (**Figure 7**). It is the area, not the magnetic field strength that changes, so the equation becomes:

$$\varepsilon = -N\frac{B\Delta A}{\Delta t}$$

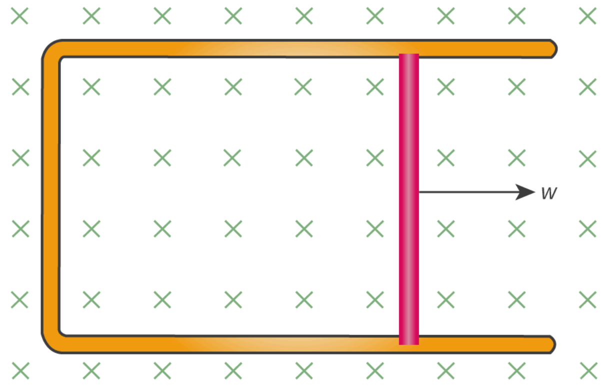

Figure 7. A conducting rod rolling along two contacts causes the area of the loop to increase, inducing an emf.

More information for figure 7

The image is a diagram illustrating a conducting rod moving along two parallel contacts. The rod is positioned vertically and rolls to the right, causing the area of the rectangular loop it forms with the contacts to increase. This movement induces an electromotive force (emf) as depicted by the equation (\varepsilon = - N\dfrac{{B\Delta A}}{{\Delta t}}). The background shows a series of green 'X' marks representing the magnetic field perpendicular to the plane of the loop. The width of the rectangle is labeled as (w), and arrows indicate the direction of motion.

[Generated by AI]

The area of the rectangle in **Figure 7** is given by the width, w, multiplied by the length, L. The length is changing because the rod is moving at velocity, v. This velocity is the rate of change of displacement (rate of change of width):

$$v = \frac{\Delta w}{\Delta t}$$

The rate of change of the area, A, is changing by:

$$\begin{aligned}\frac{\Delta A}{\Delta t} &= \frac{L\Delta w}{\Delta t}\\ &= vL\end{aligned}$$

The induced emf is given by:

$$\begin{aligned}\varepsilon &= -N\frac{B\Delta A}{\Delta t}\\ &= -NBvL\end{aligned}$$

As we are only concerned with the magnitude, not the direction, of the induced emf, we can ignore the minus sign.

When a single rod ($N = 1$) is moving at right angles to a magnetic field, the equation for induced emf is as shown in **Table 2**.

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view

Table 2. Equation for induced emf for a single rod moving at right angles to a magnetic field.

Equation	Symbols	Units
$\varepsilon = BvL$	ε = induced emf	volts (V)
	B = magnetic field strength	tesla (T)
	v = velocity of moving conductor	metres per second (m s^{-1})
	L = length of moving conductor	metres (m)

Worked example 2

A 1.0 m metal bar falls at a constant speed of 45 m s^{-1} vertically through a 3.0 T magnetic field. The length of the bar is at 90° to the direction of the magnetic field. An emf is induced in the bar. Explain why an emf is induced in the bar, and determine the magnitude of the emf.

The area through which the metal bar falls increases. (This is just like the area in **Figure 7**, but the bar is falling instead of rolling.) The area is increasing so the amount of magnetic flux passing through this area is also increasing. A change of magnetic flux induces an emf.

$$L = 1.0 \text{ m}$$

$$v = 45 \text{ m s}^{-1}$$

$$B = 3.0 \text{ T}$$

$$\begin{aligned} \epsilon &= BvL \\ &= 3.0 \times 45 \times 1.0 \\ &= 135 \text{ V} \\ &= 140 \text{ V } (2 \text{ s.f.}) \end{aligned}$$

Coil rotating

The drawback with moving the magnetic field, moving the conductor or changing the area to induce an emf is that there is an end point – the conducting rod will reach the end of the contacts, or the coil will move past the magnetic field. With a **rotating** coil, we can induce an emf without these constraints.

Magnetic field strength is a vector, so when the coil in **Figure 8** rotates, the direction in which the magnetic field intersects the coil changes continually. This would cause the strength of the field to fluctuate between B and $-B$ as it rotates through 180°, thus giving a $2B$ change in magnetic field strength.

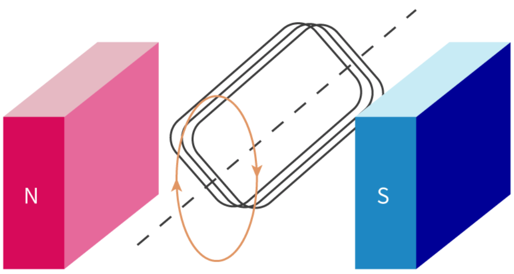

Figure 8. A coil rotating in a magnetic field causes a change in magnetic flux and induces an emf.

More information for figure 8

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The diagram illustrates a coil situated between two rectangular prisms with labeled poles 'N' and 'S', representing a magnetic north and south pole. The coil is shown at an angle between the two poles, suggesting rotation along a central axis. Arrows in the diagram depict the direction of possible rotation of the coil, which aligns with the magnetic field lines between the north and south poles. As the coil rotates, it changes its orientation relative to the magnetic field, which consequently induces an electromotive force (emf) due to the change in magnetic flux.

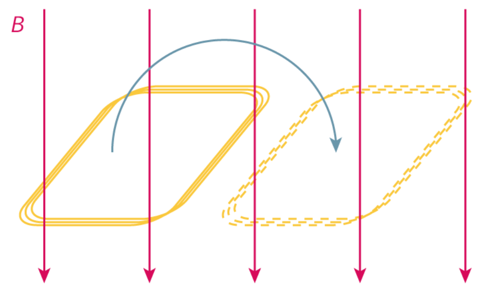
[Generated by AI]

From the perspective of the coil, the magnetic field is changing, so the equation for emf becomes:

$$\begin{aligned}\varepsilon &= -N\frac{\Delta\Phi}{\Delta t}\\ &= -N\frac{\Delta BACos\theta}{\Delta t}\end{aligned}$$

Worked example 3

A square coil of wire with 10 turns and a side length of 15 cm is rotated 180° inside a magnetic field in 50 ms. The magnetic field strength is 4.2 mT.



More information

The image shows a diagram illustrating the movement of a square coil of wire within a magnetic field. The diagram includes two main positions of the coil, one solid and one dashed, representing its initial and final positions after being rotated 180°. There are vertical arrows to indicate the direction of the magnetic field. The labels show 'B' for magnetic field and a curved arrow above the coil indicates the direction of rotation. The diagram represents the process of inducing an electromotive force (emf) by rotating the coil within the magnetic field.

[Generated by AI]

Calculate the magnitude of the emf induced in the coil.

$$N = 10$$

$$\begin{aligned}A &= 0.15^2\\ &= 0.0225\ \mathrm{m}^2\end{aligned}$$

$$\begin{aligned}\Delta t &= 50\ \mathrm{ms}\\ &= 5.0\times10^{-2}\ \mathrm{s}\end{aligned}$$

If a coil is rotated 180°, the direction of the magnetic field is reversed. Because magnetic field strength is a vector, this means it changes from $4.2\ \mathrm{mT}$ to $-4.2\ \mathrm{mT}$:

$$\begin{aligned}\Delta B &= 4.2-(-4.2)\\ &= 8.4\ \mathrm{mT}\\ &= 8.4\times10^{-3}\ \mathrm{T}\end{aligned}$$

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$$\begin{aligned}\varepsilon &= -N\frac{\Delta BA}{\Delta t}\\ &= -10 \times \frac{8.4 \times 10^{-3} \times 0.0225}{5.0 \times 10^{-2}}\\ &= -0.0378\ \text{V}\\ &= 0.038\ \text{V (2 s.f.)}\end{aligned}$$

The question only asks for magnitude, so you do not need to include the minus sign in the answer.

International Mindedness

Many discoveries, and the resulting technologies, have changed the world. Faraday's experiments have led to societies dependent on electricity generation. These discoveries and inventions are not copyrighted by large corporations, but are free for anyone to use. The World Wide Web was invented by scientist Tim Berners-Lee while he was working at CERN, and he gave it away for free. The sharing of these great scientific breakthroughs enables new discoveries and inventions.

If a company makes money from a discovery or an invention, then it can use that money to develop the technology further. Because of the success of their copyrighted technology, Google launched the Lunar XPRIZE in 2007 and offered a US$30 million prize to anyone who could land a robotic spacecraft on the Moon.

There will always be a debate about whether valuable scientific discoveries or inventions should be public domain or not. At the moment, it is up to the person, or company, who discovers or invents them first.

5 section questions

Question 1

HL Difficulty:

A nail of length L rolls along a flat table. Its initial velocity is v. At this point, the emf induced in the nail is G. After a short period of time, the velocity decreases to $\frac{v}{3}$. The emf induced at this point is H.

Deduce $\frac{G}{H}$.

The magnetic field of the Earth is constant and perpendicular to the velocity of the nail.

1 3 ✓

2 $\frac{1}{3}$

3 9

4 $\frac{1}{9}$

Explanation

$\varepsilon = BvL$

Write out the equation for each situation:

$G = BvL$

$H = B\frac{v}{3}L$

Student view

Make them equal to the same constant:

$$G = BvL$$

$$3H = BvL$$

Equate them and find the ratio:

$$G = 3H$$

Question 2

HL Difficulty:

A permanent magnet is moved at a constant speed through a coil with a large number of turns, N. What is the induced emf equivalent to?

1 The rate of change of magnetic flux through the coil multiplied by N ✓

2 The rate of change of magnetic flux through the coil

3 The instantaneous magnetic flux through the coil multiplied by N

4 The instantaneous magnetic flux through the coil

Explanation

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$$

This is the rate of change of magnetic flux multiplied by N.

Question 3

HL Difficulty:

A drone of width 3.00 m is flying horizontally at a speed of 1.50 × 10^2 m s^{-1}. The Earth's magnetic field at this point is 50.0 μT, perpendicular to the direction of the velocity of the drone. What is the induced emf between each side of the drone?

1 22.5 mV ✓

2 0.0225 mV

3 0.0225 MV

4 22.5 MV

Explanation

$$\begin{aligned} B &= 50.0\ \mu\text{T} \\ &= 5.00\times10^{-5}\ \text{T} \end{aligned}$$

$$v = 1.50\times10^{2}\ \text{m s}^{-1}$$

$$L = 3.00\ \text{m}$$

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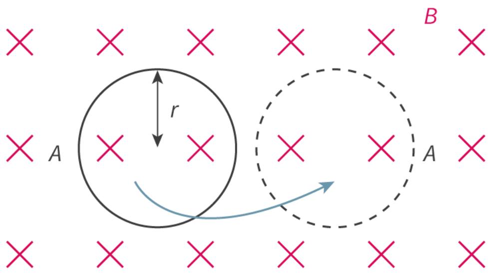
$$\begin{aligned} \varepsilon &= BvL \\ &= 5.00\times10^{-5}\times1.50\times10^{2}\times3.00 \\ &= 2.25\times10^{-2}\ \mathrm{V} \\ &= 22.5\ \mathrm{mV}\ (3\ \mathrm{s.f.}) \end{aligned}$$

Question 4

HL Difficulty:

A circular coil of wire with 100 turns is rotated 180° inside a constant magnetic field. The rotation takes 0.020 s, and the radius of the coil is 20.0 mm. An emf of 140 mV is induced.



More information

Determine the magnitude of the magnetic field strength.

1 11 mT ✓

2 22 mT

3 0.70 mT

4 11 μT

Explanation

$$N = 100$$

$$\Delta t = 0.020\ \mathrm{s}$$

$$\begin{aligned} r &= 20.0\ \mathrm{mm} \\ &= 0.02\ \mathrm{m} \end{aligned}$$

$$\begin{aligned} \varepsilon &= 140\ \mathrm{mV} \\ &= 0.14\ \mathrm{V} \end{aligned}$$

$$\begin{aligned} A &= \pi r^2 \\ &= \pi\times0.02^2 \\ &= 1.257\times10^{-3}\ \mathrm{m}^2 \end{aligned}$$

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$$

The magnetic field is changing from B to $-B$, so the change in magnetic field strength through the coil is $2B$.

$$\varepsilon = -N\frac{2BA}{t}$$

$$\begin{aligned} B &= -\frac{\varepsilon t}{2AN} \\ &= -\frac{0.14\times0.020}{2\times1.257\times10^{-3}\times100} \\ &= 0.011\ \mathrm{T} \\ &= 11\,\mathrm{mT}\ (2\ \mathrm{s.f.}) \end{aligned}$$

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Question 5

HL Difficulty:

An electric generator contains a coil with 30 turns and an area of 50.0 cm^2 in a magnetic field of strength 5.5 mT. The generator is required to produce a mean emf of 1.2 V. Determine the frequency of rotation.

1 360 Hz ✓

2 3.6 Hz

3 730 Hz

4 7.3 Hz

Explanation

$$N = 30$$

$$\begin{aligned} A &= 50.0 \text{ cm}^2 \\ &= 0.005 \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \Delta B &= 5.5 \text{ mT} \\ &= 5.5 \times 10^{-3} \text{ T} \end{aligned}$$

$$\varepsilon = 1.2 \text{ V}$$

In half of one cycle, the coil moves through 180°. As it does this, the magnetic field is reversed:

$$\Delta B = B - (-B) = 2B$$

The frequency is the number of cycles per second, $\frac{1}{T}$ where T is the time period, the time for one complete cycle.

Calculate the time needed for half a cycle to occur in order to produce the emf, then calculate the frequency.

$$\varepsilon = -N\frac{\Delta BA}{\Delta t}$$

$$\varepsilon = -N\frac{2BA}{\Delta t}$$

$$\begin{aligned} \Delta t &= -N\frac{2BA}{\varepsilon} \\ &= -30 \times \frac{2 \times 5.5 \ \times 10^{-3} \times 0.005}{1.2} \\ &= 1.375 \times 10^{-3} \text{ s} \end{aligned}$$

This is the time that half a cycle needs to be completed in, so the time for a full cycle is:

$$\begin{aligned} T &= 1.375 \times 10^{-3} \times 2 \\ &= 2.75 \times 10^{-3} \end{aligned}$$

$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{2.75 \times 10^{-3}} \\ &= 363.6 \text{ Hz} \\ &= 360 \text{ Hz (2 s.f.)} \end{aligned}$$

Student view

(The emf is the mean emf. The emf produced by a rotating coil gives a **sinusoidal** emf, so the average output emf is lower than the maximum (peak) value of the emf. This is outside the scope of DP physics.)

Lenz's law (HL)

Higher level (HL)

Learning outcomes

At the end of this section, you should be able to:

- Understand the minus sign in the equation for induced emf:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$$

- Explain the direction of induced current with reference to conservation of energy.

Look at this electromagnetic induction simulation (https://ophysics.com/em11.html) (**Interactive 1**). You can examine the result of moving the magnet either manually or sinusoidally. The bulb lights because of the magnetic flux changing inside the coil, which you can observe if you show the magnetic field.

Where does the energy come from that makes the bulb light? Can we power devices with no energy input?

Conservation of energy

The answer to the question above is no. Energy cannot be created or destroyed so it must come from somewhere. Look at **Figure 1**.

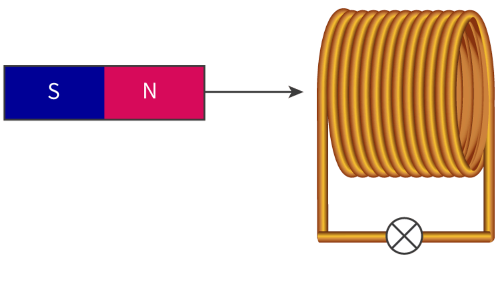

Figure 1. A bar magnet moving towards a coil of wire.

More information for figure 1

The image shows a bar magnet with two sections, labeled 'S' for south and 'N' for north, positioned horizontally. To the right of the magnet is a coiled wire connected to a circular component at the bottom, likely representing a galvanometer or similar device. An arrow between the magnet and the coil suggests movement of the magnet towards the coil. The arrangement implies the concept of electromagnetic induction, where moving the magnet generates current in the coil.

[Generated by AI]

Overview
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We have to do work to keep the bar magnet moving at a constant rate. To understand why, consider what is happening:

- as the bar magnet enters the coil, it induces a current
- as the current flows through the coil, producing a magnetic field, which causes the coil to behave like a bar magnet.

As the north pole of the bar magnet approaches the coil from the left, what would happen if the left-hand side of the coil became a magnetic south pole? The bar magnet would be attracted to the coil and would accelerate, gaining kinetic energy. At the same time, an emf would be induced, producing electrical potential energy. This would violate the law of conservation of energy, so this does not happen.

What would happen if the left-hand side of the coil became a magnetic north pole? There would be a repulsive force between the bar magnet and the coil, which would decelerate the bar magnet, reducing its kinetic energy. The kinetic energy is transferred to electrical potential energy through induction. This does **not** violate the law of conservation of energy, so this is what happens.

This principle can be applied more broadly, and it is known as Lenz's law.

Concept

Lenz's law states that an induced current (and emf) will always act to oppose the change that caused it.

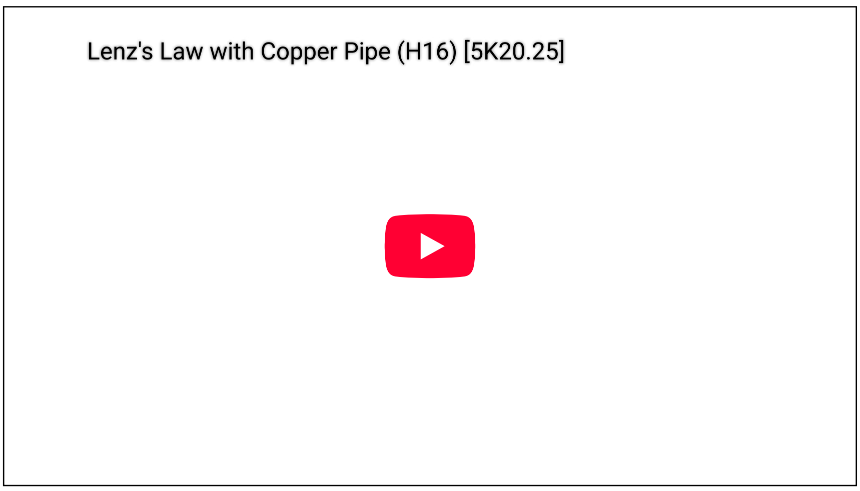
The equation for induced emf, $\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$, has a minus sign, which tells us that the direction of the induced emf is opposite to the direction of the change in magnetic flux.

Lenz's law can tell us which direction the current will flow around the coil as the magnet approaches in **Figure 1**. The current will flow in the direction that produces a north pole on the left side of the coil.

Look again at the simulation in **Interactive 1**. The red arrow shows the direction of the induced current. What happens after the magnet passes through the centre of the coil?

As the magnet is moving away, the induced current is again obeying Lenz's law and trying to oppose the change causing it. The magnet is moving away from the coil, so the magnetic field produced by the induced current wants to stop this change, and it produces an attractive force. The direction of the current has reversed in order to do this.

Look at **Video 1** to see a demonstration of Lenz's law.



Video 1. Demonstration of Lenz's law.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

More information for video 1

This video offers a captivating visual demonstration of Lenz's Law by showing a simple yet powerful experiment involving a vertical copper pipe and two balls of the same size. The setup is straightforward but highlights some fascinating physics in action.
The video begins with a professor dropping a regular iron ball into a copper pipe clamped to a table. As expected, the ball falls straight through the pipe very quickly, taking only about 0.02 seconds to exit from the bottom. This part shows how a non-magnetic object is not affected by the pipe and simply falls under the force of gravity.
Next, a spherical magnet of the same size is dropped into the same copper pipe. This time, something surprising happens—the magnet doesn't just fall straight through. Instead, it moves very slowly, taking nearly 4 seconds to reach the bottom. At first glance, it seems like the pipe is somehow resisting the magnet's fall, even though nothing is physically touching it.
The video then pauses to explain what's really going on with the help of text:
"HOW DOES IT WORK?
The falling magnet induces a current within the tube.
By Lenz's Law, the current creates a magnetic field that opposes the field of the falling magnet. Thus, the magnet feels a resistive force and falls more slowly!"
Later in the video, a top-down view shows the magnet slowly traveling through the pipe, making this invisible process more understandable.
There's no friction, no strings, and no mechanical brakes—just the invisible power of electromagnetic induction at work.

Table 1 shows examples of different situations where we can apply Lenz's law to deduce the direction of current flow. In many cases, the right-hand slap rule can also be used to predict the current direction – but it needs to be applied differently when predicting current direction. When predicting the direction of the force on a current-carrying conductor in a magnetic field (as in section D.4.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/inducing-an-emf-hl-id-46424/)), the thumb points in the direction of the current (the 'cause') and the hand slaps in the direction of the force (the 'effect'). When predicting the direction of an induced current, the thumb points in the direction of the motion (the 'cause') and the hand slaps in the direction of the current (the 'effect'). **Figure 2** summarises this.

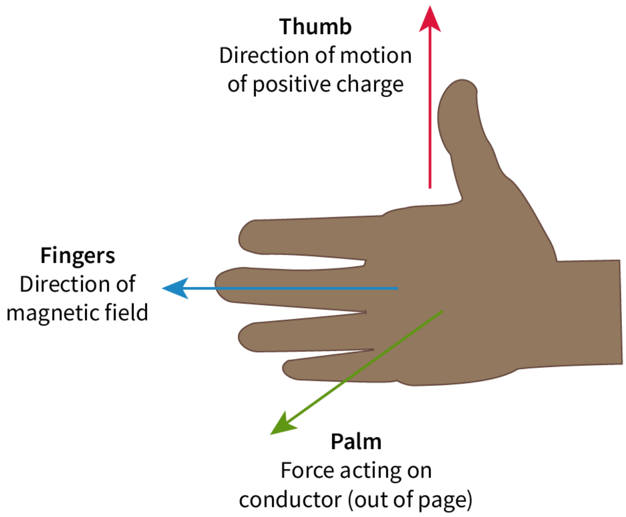


Figure 2. The right-hand slap rule for predicting the direction of force (on a current-carrying conductor in a magnetic field) or current (in a conductor moving in a magnetic field).

More information for figure 2

The image shows an illustration of the right-hand slap rule used in physics to predict the direction of force or current in magnetic fields. It features an open right hand with specific directions labeled:

- **Thumb**: Labeled "Direction of motion of positive charge," pointing upwards.
- **Fingers**: Labeled "Direction of magnetic field," pointing left.
- **Palm**: Labeled "Force acting on conductor (out of page)," pointing outwards towards the viewer.

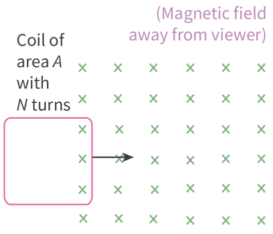
The illustration visually explains how the hand orientation predicts the force direction on a current-carrying conductor in a magnetic field by using the thumb, fingers, and palm as guides for charge movement, magnetic field, and resultant force, respectively.

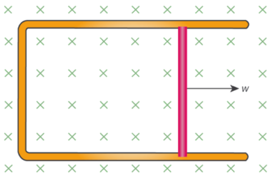
Student view

[Generated by AI]

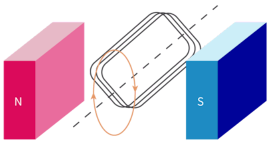
Remember that the direction used for current is the conventional current direction (which is opposite to the direction of flow of electrons).

Table 1. Applying Lenz's law and the right-hand slap rule to deduce the directions of induced currents.

Situation	Prediction using right-hand slap rule	Explanation using Lenz's law
A coil of wire moving into a magnetic field:  More information The diagram illustrates a coil of wire moving into a magnetic field, depicted by an array of green crosses. The coil, labeled as having an area 'A' and 'N' turns, is represented by a pink rectangle on the left side of the image. An arrow points from the coil into the array of green crosses, indicating the direction of movement. Above the array of crosses, the text reads "Magnetic field away from viewer," suggesting that the field is directed into the plane of the image. The crosses symbolize the magnetic field lines. [Generated by AI]	Choose a side of the coil that is cutting through lines of flux — in this case, the front of the coil. Hold your right hand flat and point your fingers in the direction of the magnetic field (into the page). Point your thumb in the direction of movement (to the right). If you slap your hand, your palm moves upwards, so the current in this part of the coil is directed upwards. Therefore the current in the coil is anticlockwise.	The coil is moving into the field, so the magnetic flux through the coil is increasing. The current induced in the coil opposes this change by producing a magnetic field directed out of the page. The induced current is therefore anticlockwise.

Situation	Prediction using right-hand slap rule	Explanation using Lenz's law
Rod rolling along a metal frame:  More information The image is a diagram illustrating a rod rolling along a rectangular metal frame. The frame is drawn with orange lines forming a rectangle. Inside the frame, there is a pink cylindrical rod positioned vertically. An arrow labeled 'W' is pointing from the right side of the rod, indicating a rolling direction or force applied. The background of the image consists of a grid of green X marks, possibly representing the force field or environment in which the rod is located. The diagram might be used to visualize the motion of the rod and interactions with the frame. [Generated by AI]	Apply the right-hand slap rule to the rod: fingers into the page, thumb to the right, and palm moves upwards. Therefore the current in the rod is up the page (and the current in the whole circuit is anticlockwise).	As the rod rolls to the right, the flux through the loop increases. As in the situation above, the current induced in the loop opposes this change by producing a magnetic field directed out of the page. The induced current is therefore anticlockwise and the current in the rod is directed upwards.

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Situation	Prediction using right-hand slap rule	Explanation using Lenz's law
Rotating coil:  More information The diagram shows a rotating coil placed between two blocks labeled 'N' and 'S', indicating the north and south poles, respectively. The coil is depicted as a rectangular loop on a dotted axis, suggesting its rotation in a circular motion. The direction of rotation is marked by a pair of curved arrows encircling the coil. The north pole block is colored pink, while the south pole is shaded in a gradient of blue. This arrangement visually represents the fundamental concept of electromagnetic induction, where the rotation of the coil within the magnetic field between the two poles generates an electric current. [Generated by AI]	Choose a side of the coil that is cutting through field lines — that is, one of the two longer sides. For the upper of these sides, point your fingers to the right (in the field direction) and your thumb up (in the direction in which the wires are cutting through field lines). Your palm slaps forwards into the page, so the current in the upper long side is into the page. Therefore the current in the coil is clockwise (as viewed from the south pole of the permanent magnet).	The magnetic field lines point from left to right (from north to south). The coil is rotating clockwise, so at the instant shown the flux through the coil is increasing. The induced current produces a magnetic field that opposes this change, so it points from right to left. The current direction must therefore be clockwise (as viewed from the south pole of the permanent magnet).

Consider one more situation: a magnet moving towards the end of a circular coil (or equivalently, a coil moving towards a magnet), as shown in **Figure 3**.

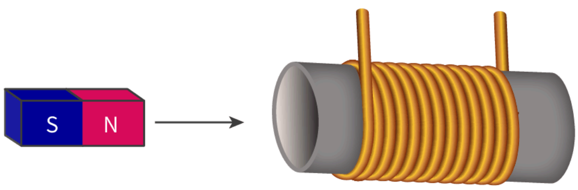


Figure 3. A bar magnet moving towards a circular coil.

More information for figure 3

The image depicts a bar magnet with its north (N) and south (S) poles labeled. It is moving towards a circular coil made of coiled wire, indicated by an arrow pointing from the magnet to the coil. The magnet is colored with a blue section for the south pole and a red section for the north pole. The coil is depicted in a yellow color and is wrapped around a grey cylindrical core. The direction of motion is indicated by a black arrow between the magnet and the coil.

[Generated by AI]

It is less straightforward to apply the right-hand slap rule here, because the wires are curved instead of straight, and the magnetic field is not uniform. It is easier to use Lenz's law to predict the current direction.

Student view

Overview
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First, recall the shape of the magnetic field lines for a coil (**Figure 4**). The field lines outside the coil point from north to south, but the field lines inside the coil are in the opposite direction.

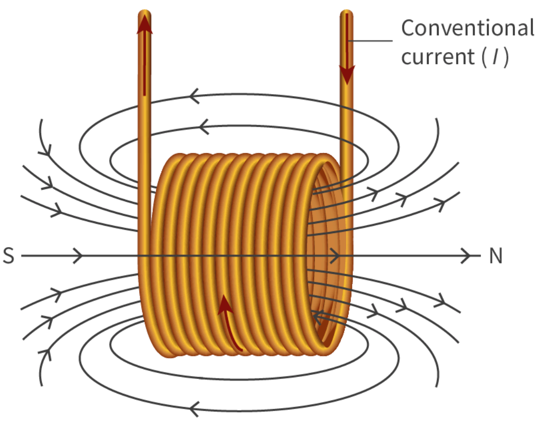

Figure 4. Magnetic field lines around a current-carrying coil.

More information for figure 4

The diagram shows a coil with copper-colored wires wound in a cylindrical shape. Two vertical wires extend from the top of the coil. Arrows along the wires indicate the direction of conventional current flow: upwards on the left wire and downwards on the right wire. Around the coil, there are several magnetic field lines which are represented by curved arrows. Outside the coil, these magnetic field lines curve from left (south) to right (north), whereas inside the coil, the field lines curve in the opposite direction. The diagram labels "Conventional current (I)" next to the right-hand side wire. The diagram visually illustrates how the current flowing through the coil generates a magnetic field with distinct north (N) and south (S) poles.

[Generated by AI]

Lenz's law states that the current induced in the coil produces a magnetic field that opposes the magnet's motion. The left side of the coil in **Figure 4** will therefore be a north pole, so that the magnet experiences repulsion. For this to happen the current must flow clockwise as viewed from the left-hand end of the coil. The coil therefore behaves as if its left-hand end is connected to a positive terminal (even though it is not) and its right-hand end is connected to a negative terminal.

Study skills

It is possible to predict which end of a coil is which pole by using a simple rule. Remember that we are talking about conventional current in these examples (charge carriers moving from positive to negative).

Imagine looking at the coil from the end:

- If the current moves anticlockwise, then the end of the coil is a north pole.
- If the current moves clockwise, then the end of the coil is a south pole.

Student view

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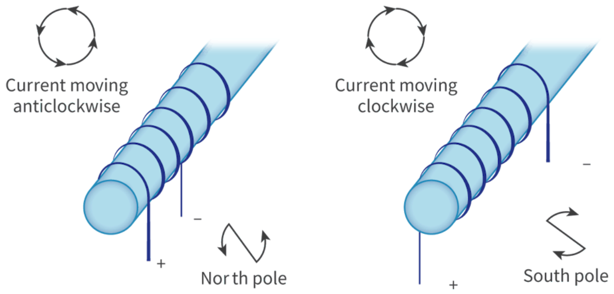

Figure 5. How to identify the north and south poles of a coil.

More information for figure 5

This diagram illustrates the concept of identifying the north and south poles of a coil based on the direction of the electric current. There are two main segments in the image. On the left, the coil is shown with rings and an arrow indicating the current moving anticlockwise. Below this, a label denotes that this orientation creates a north pole at the front end of the coil. On the right side, the coil shows rings with an arrow indicating the current is moving clockwise. In this setup, the south pole is created at the front end of the coil. Text labels are included to indicate the direction of the current and the respective poles formed (north and south).

[Generated by AI]

Worked example 1

A metal bar connected to a resistor falls vertically into a magnetic field. The bar's length is perpendicular to the field lines.

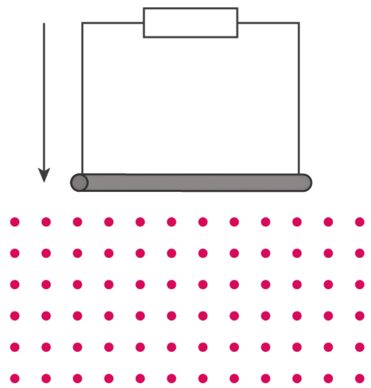

Figure 6. A metal bar falling into a uniform magnetic field.

More information for figure 6

The image depicts a diagram of a metal bar that is falling vertically into a magnetic field. The magnetic field is represented by an array of uniform dots. The metal bar appears connected at the top to a rectangular component, which is likely a resistor. An arrow next to the bar indicates the direction of motion, showing that the bar is moving downward into the field. The length of the bar is perpendicular to the magnetic field lines. This setup is part of a circuit where the direction of current flow is to be predicted as the bar enters the field.

[Generated by AI]

Predict the direction of current flow in the circuit (clockwise or anticlockwise) as the bar enters the field.

Student
view

Since the question asks you to predict but not explain, you can use any method for predicting the induced current direction (including Lenz's law, the right-hand slap rule, and Fleming's right-hand rule). Note that only Lenz's law can offer an explanation as well as a prediction.

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Method 1 (using the right-hand slap rule):

If you hold the right hand flat and point the fingers out of the page (field direction) and the thumb downwards (motion direction), the palm slaps towards the left. This shows the direction of the current in the bar. The current in the loop is therefore clockwise.

Method 2 (using Lenz's law):

As the bar enters the field, the magnetic flux within the circuit loop increases, causing an induced current. The current produces a magnetic field that opposes the change, so it must produce a magnetic field that points into the page.

Therefore the loop has a north pole at the rear (the face we cannot see). Applying the same rule as for a coil, we find that the current in the loop must be clockwise.

Self-induction

There is another example of induction we have not considered yet – self-induction. Carry out the activity to explore self-induction using a thought experiment.

Theory of Knowledge

Thought experiments are hypothetical or imagined situations that help to test or explore a theory. They are a useful way of thinking about variables that are hard (or impossible) to change, and for visualising extreme examples.

One of Einstein's famous thought experiments was to imagine what it would look like if you were travelling at the speed of light next to a beam of light. This was physically impossible to do, but the thought experiment helped give him insight into what became the theory of relativity.

Select a suitable artefact and use the ideas in this subtopic to formulate a 60-second verbal response to the following TOK exhibition prompt:

What role does imagination play in producing knowledge about the world?

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 10—15 minutes
- **Activity type:** Individual activity

Imagine a circuit with a coil of wire with many turns. It is connected in series with a bulb, a cell and a switch, which you can open and close.

1. When the switch is open, what will the magnetic field around the coil look like?
2. When the switch is closed, what will the magnetic field around the coil look like?
3. What is the difference between these two situations?
4. What can you deduce about what happens to the current in the coil at the moment the switch is opened and closed?

You might choose to just think about this, or you might choose some of these tools to help scaffold your thinking:

- mini whiteboards to draw each of the situations

Student view

Overview
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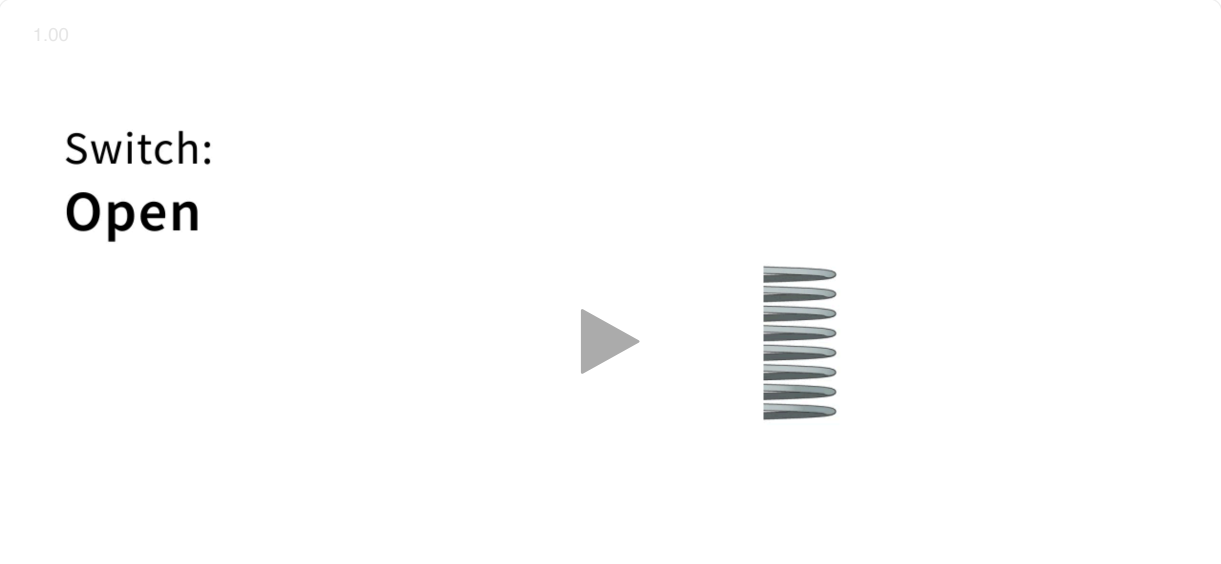
- tracing paper, so you can overlay situations 1 and 2
- an electrical circuit.

In the activity, we thought about a coil of wire being connected to then disconnected from a cell. The magnetic field as we open and close the switch might look like the diagram in **Interactive 1**.



Interactive 1. Magnetic Field When Switch Is Opened and Closed.

More information for interactive 1

The animation video illustrates the formation of a magnetic field around a coil of wire when a switch is closed. Initially, when the switch is open, there is no visible magnetic field around the coil. The coil appears as a simple set of loops without any surrounding field lines. Later the switch is closed, allowing current to flow through the coil. When the switch is closed, the current flow results in the formation of a magnetic field, which is depicted by blue concentric field lines emerging from the coil and extending outward. The visualization effectively demonstrates the relationship between electric current and the generation of a magnetic field, highlighting the concept of electromagnetic induction.

When a current flows in the coil, a magnetic field is produced around (and inside) the coil. Inside the coil of wire, there is a changing magnetic flux as we open or close the switch – no magnetic flux when the switch is open, and a non-zero magnetic flux when the switch is closed. A changing magnetic flux induces an emf. So, by opening and closing the switch, the coil is inducing an emf (sometimes called a 'back emf') in itself. This is called self-induction.

Figure 7 shows the approximate shapes of graphs against time of: the potential difference across the coil in the absence of electromagnetic induction; the induced emf across the coil; and the actual potential difference across the coil. What would a current–time graph for the coil look like?

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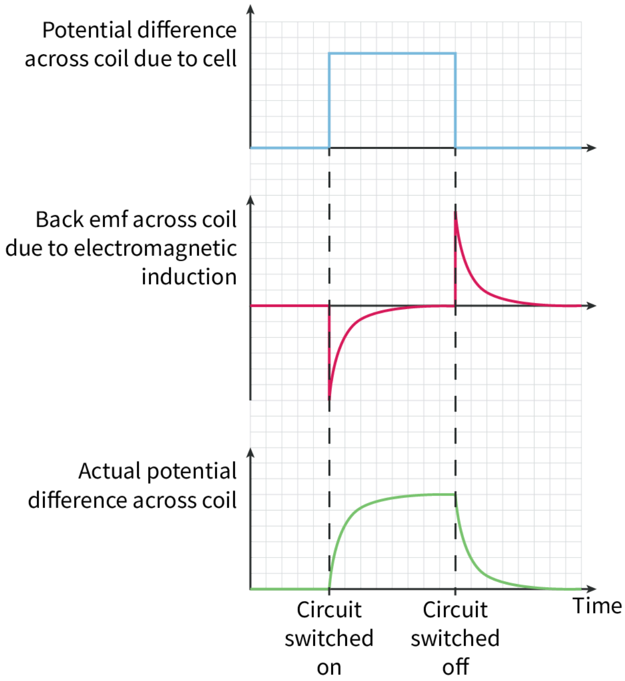

Figure 7. Graph of potential difference and back emf against time for a coil in a circuit.

More information for figure 7

The image is a graph showing the potential difference and back electromotive force (emf) against time for a coil in a circuit. The graph has three distinct curves:

1. **Potential Difference Across Coil Due to Cell:** Represented by a light blue curve, which starts at a higher voltage, remains constant, and then decreases sharply when the circuit is switched off.
2. **Back emf Across Coil Due to Electromagnetic Induction:** Shown in red, starting from zero, it spikes negatively when the circuit is switched on, then rises sharply to a positive peak before gradually decreasing back to zero.
3. **Actual Potential Difference Across Coil:** Illustrated in green, this curve begins at zero, increases sharply when the circuit is switched on, reaching a peak, and then decreases gradually over time.

The X-axis represents time, marked by two key events: "Circuit switched on" and "Circuit switched off." The Y-axis represents different voltages or emfs related to the coil.

[Generated by AI]

Work through the activity to check your understanding of Lenz's law.

Activity

- **IB learner profile attribute:** Open-minded
- **Approaches to learning:** Communication skills — Delivering constructive criticism appropriately
- **Time required to complete activity:** 50 minutes
- **Activity type:** Pair activity

Lenz's law predicts the direction of the force when a magnetic field and a conductor are moving relative to each other. You are going to perform a small experiment (or watch a video of the experiment) and see if you can explain the results using your knowledge of Lenz's law.

Instructions

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view

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1. Find a strong magnet (the stronger the better!) and suspend it on the end of a string like a pendulum bob.
2. Swing the pendulum. It should swing normally.
3. Underneath the bottom of the pendulum (but not close enough to touch), place a block of aluminium, copper or some aluminium foil.
4. Try to get the aluminium to stick to the magnet — it shouldn't work — aluminium is not a magnetic material.
5. Swing the pendulum again, with the aluminium underneath.

Questions

1. What is different about the swinging of the pendulum with the aluminium present? Why?
2. How does this relate to Lenz's law?
3. What could be some real world applications of this?

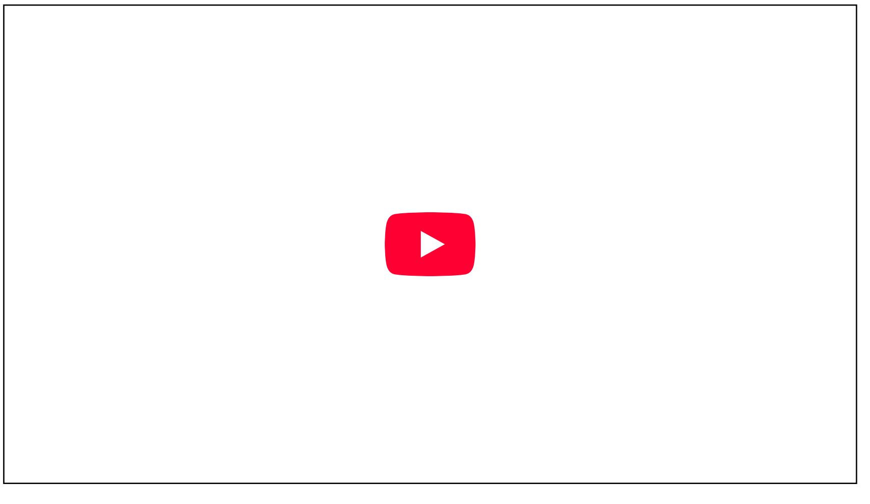
If you don't have the right equipment you can watch **Video 2** instead (pause the video before he explains what is happening).

Video 2. Lenz's law pendulum.

Outcome

In your pair, devise an explanation for what you observed. Compare it with another pair in the class — what do you agree on? What do you disagree on?

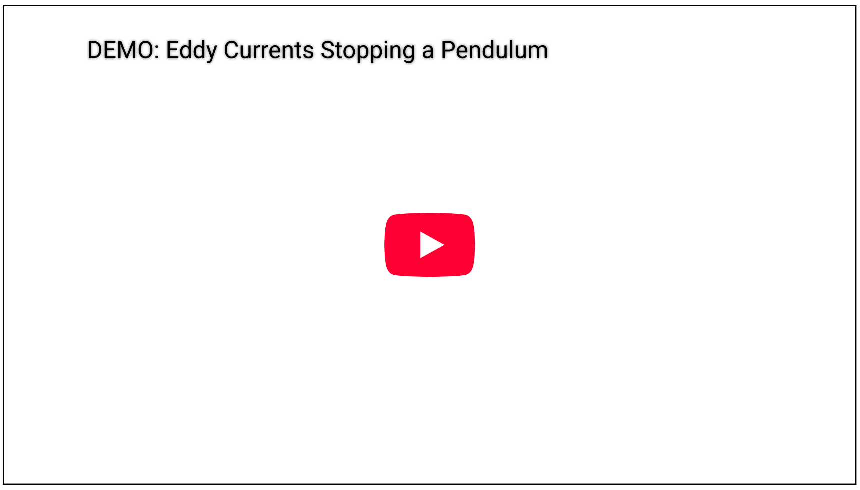
You can see the same effect in the first half of this video with some minor explanations.



Eddy currents-magnetic braking-Lenz's law.

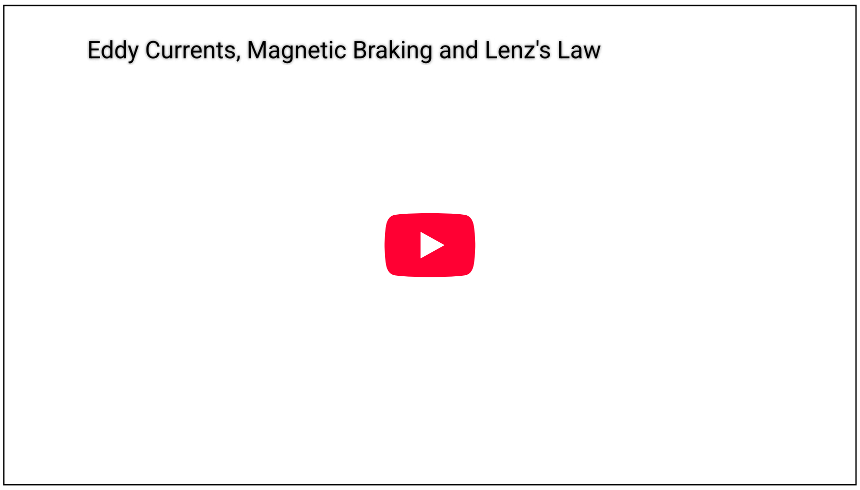
Student
view

This professor is doing a similar experiment with copper in this video and explains it more thoroughly.



Eddy currents stopping a pendulum.

This video explains a possible application of this phenomenon.



Eddy currents, magnetic braking and Lenz's law.

5 section questions

Question 1

HL Difficulty:

The north pole of a magnet is moving towards a coil. The end of the coil facing the magnet becomes a 1 north ✓ pole.

After the magnet passes through the coil, the closest pole to the coil is the south pole. The end of the coil facing the magnet as it moves away becomes a 2 north ✓ pole.

Accepted answers and explanation

#1 north
North

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#2 north
North

General explanation

When the north pole of a magnet moves towards a coil, there would be a repulsive force between the bar magnet and the coil. This would decelerate the bar magnet, reducing its kinetic energy. The kinetic energy is transferred to electrical potential energy through induction. This does **not** violate the law of conservation of energy. This can only occur if the end of the coil facing the magnet is a north pole.

As the magnet is moving away, the induced current is again obeying Lenz's law and trying to oppose the change causing it. The magnet is moving away from the coil, so the magnetic field produced by the induced current wants to stop this change, and it produces an attractive force by that side of the coil becoming the north pole.

Question 2

HL Difficulty:

True or false?

Lenz's law states that an induced current must flow in a direction that repels any magnet.

False ✓

Accepted answers

False, F, false, f

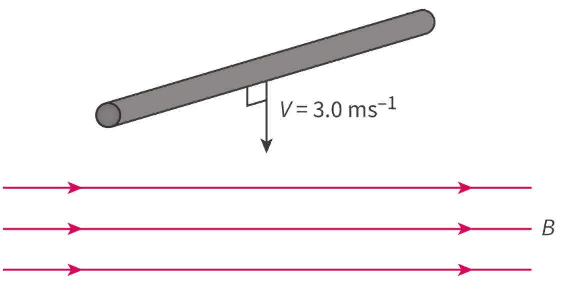
Explanation

Lenz's law states that an induced current will always oppose the change that caused it. Sometimes, this will be a repulsive force, but sometimes it will be an attractive force.

Question 3

HL Difficulty:

A horizontal metal bar is moving vertically downwards at a constant speed of 3.0 $m\,s^{-1}$ when it enters a horizontal magnetic field.



More information

What is the most likely speed of the bar within the field?

1 2.5 $m\,s^{-1}$ ✓

2 3.0 $m\,s^{-1}$

3 3.5 $m\,s^{-1}$

4 4.0 $m\,s^{-1}$

Student view

Overview
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Explanation

The bar is falling at a constant speed, so it has reached terminal velocity or there is no external supply of energy.

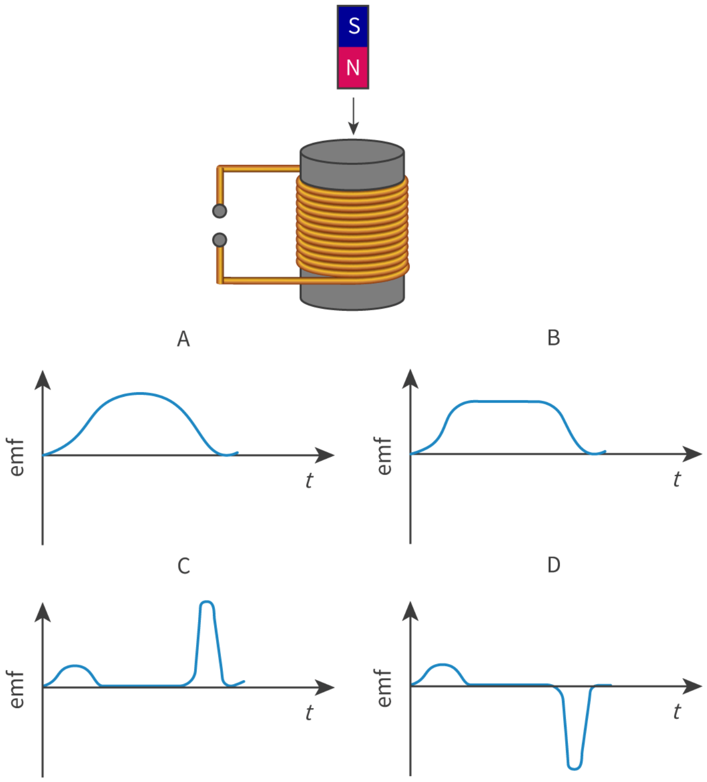
Lenz's law states that the induced current in the bar will produce a magnetic field that will oppose the change that caused it. The change is the bar entering the magnetic field. The induced current produces a magnetic field that opposes the existing magnetic field, repelling it and reducing the speed of the bar. Therefore, the speed that the bar is falling will reduce and the only viable answer option is $2.5\,m\,s^{-1}$.

(The bar does not have to be connected to a circuit for an induced current to flow. Eddy currents (small loops of current) are induced within the metal.)

Question 4

HL Difficulty:

A magnet falls vertically, from rest, through a coil. Which graph (A, B, C or D) shows the correct variation of induced emf with time, t?



More information

1 D ✓

2 A

3 B

4 C

Explanation

Emf is only induced when there is a change in magnetic flux. When the magnet is in the middle of the coil, the field is constant and so there is no change in magnetic flux and no induced emf, so A and B are not correct.

Lenz's law states that the induced current will oppose the change that caused it. When the magnet enters the coil, the magnetic flux increases. When the magnet leaves the coil, the magnetic flux decreases. These are opposite changes so the emf (and current) is in opposite directions. So C is not correct and the answer is D.

Student view

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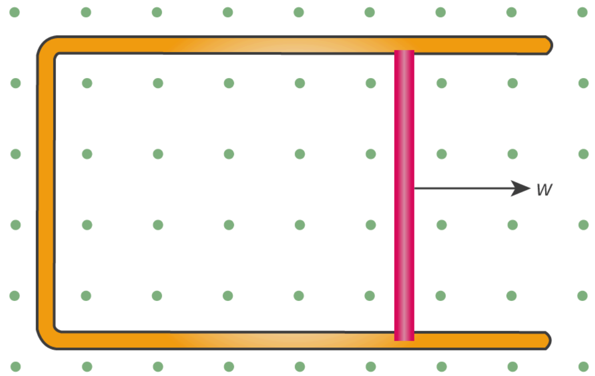
Question 5

HL Difficulty:

A metal rod is rolled along two contacts with a constant velocity. The direction of the magnetic field is out of the page.



More information

Which row of the table gives the direction of the current flow and the effect on the velocity of the rod?

	Direction of current flow	Velocity
A	Clockwise	Increases
B	Anticlockwise	Increases
C	Clockwise	Decreases
D	Anticlockwise	Decreases

1 C ✓

2 A

3 B

4 D

Explanation

According to the conservation of energy, the increase in electrical energy must be coming from a decrease in kinetic energy, so the rod will slow down.

There are two ways to determine the direction of current flow.

Using Fleming's left-hand rule on the electrons in the rolling rod. The rod is rolling to the right, so the current is to the left. The magnetic field is out of the page, so the force on the electrons in the rod is upwards. Conventional current flows downwards in the rod, which is clockwise around the loop.

Using Lenz's law: The magnetic flux passing through the loop is increasing in the out-of-the-page direction (because the area is increasing). The current tries to oppose this change and produce a magnetic field inside the coil that is into the page. This means you are looking at the south pole of the coil, so the current must flow clockwise.

Student view

AC generators (HL)

Higher level (HL)

Learning outcomes

At the end of this section, you should be able to:

- Explain the sinusoidal shape of magnetic flux and emf against time graphs for a coil rotating in a constant magnetic field.
- Identify and explain the changes in induced emf when the frequency of rotation changes in a constant magnetic field.

Almost all electricity around the world is produced by rotating a coil inside a magnetic field. There are lots of different ways of harnessing energy to rotate a coil, from wind turbines (**Figure 1**) to nuclear fission. The speed at which the coil rotates affects the emf generated. Wind turbines, for example, can turn at different speeds. How might this affect the output?

Figure 1. Wind turbines.

Rotating coils

In order to generate electricity, we need to rotate a coil of wire within a permanent magnetic field (see section D.4.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-magnetic-fields-hl-id-46423/)). For a coil of area A in a magnetic field with field strength B, the magnetic flux in each turn of the coil is given by:

$$\Phi = BA\cos\theta$$

where θ is the angle between the magnetic field direction and the normal to the coil, as shown in **Figure 2**.

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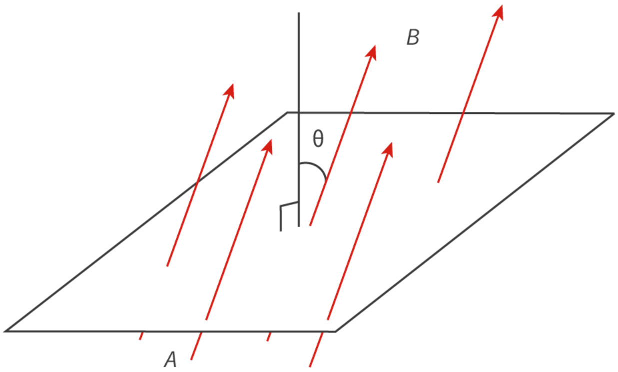

Figure 2. Magnetic flux in a coil.

More information for figure 2

The image is a diagram showing a rectangular coil in the plane of the page. Arrows labeled with 'B' represent the magnetic field lines passing through this coil from below to above. These arrows are evenly spaced and point upwards at an angle through the coil.

There is a central vertical line intersecting the coil, and at this intersection, an angle is marked as θ (theta) between the normal to the coil (perpendicular to its plane) and the direction of the magnetic field (B). The angle θ changes as the coil rotates, affecting the magnetic flux through the coil.

The base of the figure is marked with 'A', signifying the area of the coil, and the field lines show how the angle θ changes with the coil's orientation relative to the magnetic field direction.

[Generated by AI]

The number of turns in the coil, the area of the coil, and the strength of the magnetic field are all constant, so as the coil rotates, the only variable that is changing is the angle, θ. As a result, a graph of magnetic flux against time has the shape of a cosine graph, as shown in **Figure 3**. At the beginning of the cycle (A), the coil is parallel to the field (so $\theta = 90°$).

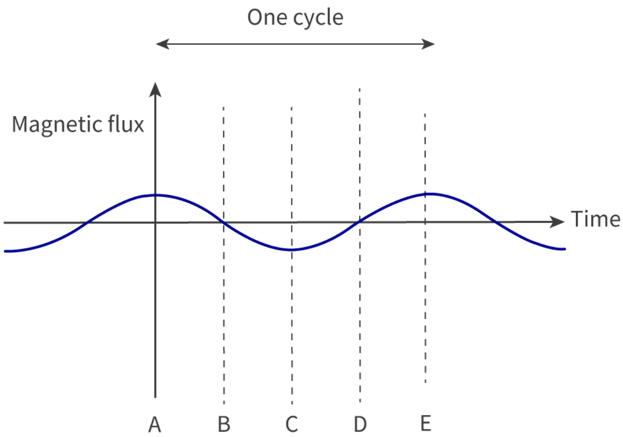

Figure 3. Magnetic flux versus time graph.

More information for figure 3

The image is a graph depicting magnetic flux against time. The X-axis represents time, marked at intervals with labels A to E. It denotes one cycle, indicated by an arrow spanning across the top of the graph. The Y-axis represents magnetic flux. The diagram shows a cosine wave indicating how magnetic flux changes over time. At point A, the wave starts at zero, peaks positively between A and B, returns to zero at C, continues to a negative peak between C and D, and rises back to zero at E, completing the cycle. The major inflection points are at A, B, C, D, and E, representing complete sections of the cosine wave cycle.

Student
view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

[Generated by AI]

According to Faraday's law, the emf induced in a closed circuit is the rate of change of magnetic flux experienced by the circuit. The rate of change of magnetic flux is equal to the gradient of the graph in **Figure 4**.

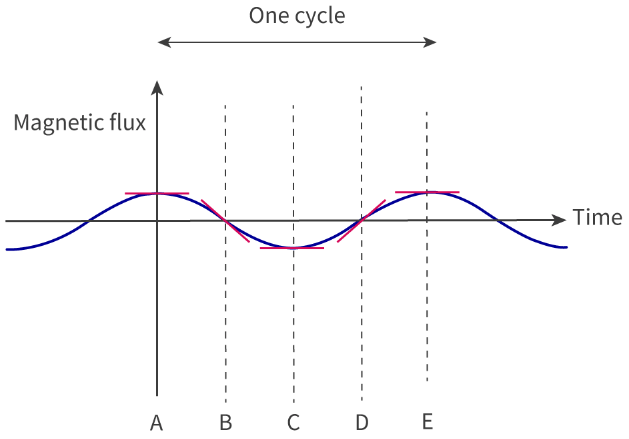

Figure 4. Magnetic flux versus time graph, showing tangents

More information for figure 4

The image depicts a graph with the X-axis labeled "Time" and the Y-axis labeled "Magnetic flux." The graph represents a sinusoidal wave, illustrating how magnetic flux changes over time. There are five key points marked on the graph: A, B, C, D, and E. Each point has a tangent line drawn, indicating the gradient at these points. The wave completes one full cycle from point A to E, highlighting the periodic nature of the flux changes. Dashed vertical lines at each point (A through E) visually separate sections of the graph and aid in demonstrating the rate of change of flux, which is central to understanding Faraday's law as described in the surrounding text.

[Generated by AI]

Figure 4 is the same graph as **Figure 3**, but tangents showing the gradients have been drawn at points A, B, C, D and E:

- At A, C and E, the gradient is zero.
- At B, the gradient is at its maximum negative value.
- At D, the gradient is at its maximum positive value.

The equation for induced emf is:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$$

By substituting the equation for magnetic flux gives:

$$\varepsilon = -N\frac{BA\ \Delta\cos\theta}{\Delta t}$$

The rate of change of a $\cos\theta$ graph is a $-\sin\theta$ graph, so a graph of emf output against time looks like the graph in **Figure 5** (notice that the two minus signs cancel each other out giving a $+\sin\theta$ graph).

Student view

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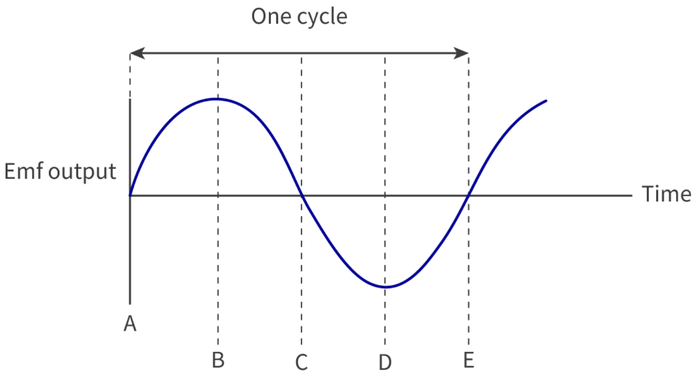


Figure 5. Emf output versus time graph.

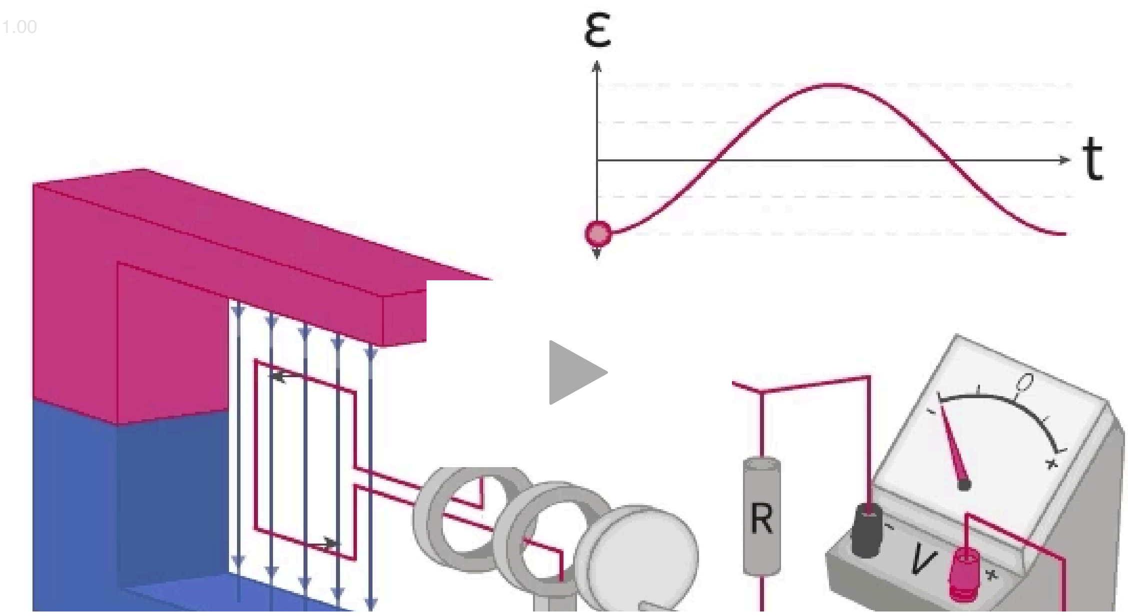
More information for figure 5

The image is a graph depicting the electromotive force (emf) output versus time. The X-axis represents time, labeled with points A, B, C, D, and E. A full cycle of the sine wave is shown, with an arrow labeled "One cycle" indicating the distance between point A and point E. The Y-axis represents the emf output. The sinusoidal curve starts at zero at point A, reaches a positive peak between A and B, returns to zero at C, drops to a negative peak between C and D, and returns to zero again at point E, completing one full cycle.

[Generated by AI]

You can see this effect with the animation in **Interactive 1.** Think about the following questions.

- What position is the coil in when the induced emf is maximum? Why?
- What position is the coil in when the induced emf is zero? Why?



Interactive 1. The Emf Output of a Rotating Coil.

More information for interactive 1

This video illustrates the working of an AC generator by showing how an electromotive force (emf) is produced in a coil rotating within a magnetic field. The setup includes a coil rotating between the poles of a magnet, with field lines passing through it. The magnet is color-coded, with the north pole in pink and the south pole in blue, indicating the direction of the magnetic field passing through the rotating coil. As the coil rotates, the magnetic flux through it changes, inducing an emf according to Faraday's law.
This rotation causes a change in the magnetic flux through the coil over time. According to Faraday's Law of Electromagnetic Induction, a changing magnetic flux induces an emf in the coil. The direction of the induced emf changes as the coil completes each half rotation, resulting in an alternating current (AC).

Student view

A key feature of the video is the inclusion of a voltmeter connected to the coil. This voltmeter measures and displays the instantaneous value of the induced emf generated across the resistor R, allowing viewers to observe how it changes in real time. The voltmeter shows both positive and negative readings, corresponding to the direction of induced emf as the coil completes its rotation. This dynamic change in polarity visually supports the concept of alternating current. Alongside this, a dynamic graph is plotted on the screen to represent the emf (ε) as a function of time (t). The resulting waveform is sinusoidal, reflecting the periodic nature of the coil's rotation and the corresponding fluctuation in magnetic flux.

The induced emf is at its maximum when the coil's sides are moving perpendicular to the magnetic field lines; this is when the rate of change of magnetic flux is greatest. Conversely, when the coil is aligned parallel to the field lines, the flux linkage is either at a peak or trough, but its rate of change is momentarily zero, and hence the induced emf drops to zero. The polarity of emf reverses every half-rotation, resulting in alternating current. This key relationship between coil orientation and emf generation is clearly illustrated in the video, reinforcing core concepts in electromagnetic induction and the operation of AC generators.

- When the induced emf is maximum, the coil is parallel to the magnetic field, and the motion of the edge of the coil is perpendicular to the magnetic field. Because of this, the magnetic flux passing through the coil is changing most rapidly, so the induced emf is maximum.
- When the induced emf is zero, the coil is perpendicular to the magnetic field and the motion of the edge of the coil is parallel to the magnetic field. Because of this, the magnetic flux passing through the coil is not changing at this instant, so the induced emf is zero.

Making connections

In circular motion (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)) and simple harmonic motion (see subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)), the angle that an object undergoing sinusoidal motion has passed through can be described using the angular velocity, ω, multiplied by the time that has passed, *t*. Applying this to the equation for induced emf gives:

$$\varepsilon = -N\frac{BA\Delta\cos\omega t}{\Delta t}$$

Differentiating this gives:

$$\varepsilon = \omega NBA\sin(\omega t)$$

This is the equation for the graph in **Figure 5**. It is not in the DP *Physics data booklet* and is outside the scope of this DP physics course.

The induced emf oscillates sinusoidally when a coil rotates in a constant magnetic field. This form of electrical power is called AC (alternating current). This is different from DC (direct current), which does not change direction.

Nature of Science

Aspect: Hypotheses

Possibly the most famous rivalry in the history of science was that between Nikola Tesla and Thomas Edison in the late 19th century. Edison was a supporter of DC electricity and Tesla felt that AC was more useful.

The two men publicly argued with and insulted each other for many years. Tesla said that AC was superior because it could be transmitted over longer distances by using a higher voltage. Edison argued that higher voltages were impractical and dangerous. In response, Tesla worked with a photographer to produce images like the one in **Figure 6**.

Overview
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In the end, both Tesla and Edison were correct. We use AC to transfer electricity over large distances using high voltages, but a lot of appliances use DC with much lower voltages.

Arguing did not prove that either Tesla or Edison was correct. Imagine the transformative technologies that might have emerged if they had worked together.

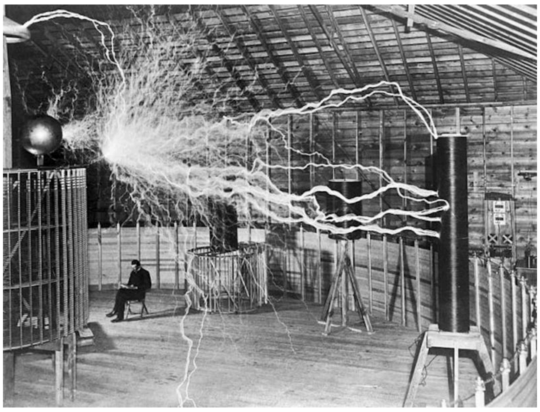

Figure 6. Tesla sitting among arcs of electricity created by his Tesla coil.

Source: Nikola Tesla, with his equipment EDIT by Photographer: Dickenson V. AlleyRestored by Lošmi (https://commons.wikimedia.org/wiki/File:Nikola_Tesla,_with_his_equipment_EDIT.jpg) is licensed under CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/)

Changing the frequency

Electrical energy is an extremely useful form of energy because we can transmit it quickly over long distances and transfer it to other forms of energy. Imagine we have two wind turbines. Each turbine is turning a coil in a permanent magnetic field, and producing a sinusoidal emf (**Video 1**). If one of the turbines is spinning faster than the other, what effect will that have?

Video 1. Wind Turbines Spinning at Different Speeds.

More information for video 1

The video shows multiple wind turbines spinning at different speeds in an open landscape. Some parts of the landscape consist of pine trees while the other part consists of an open ground with wind turbines. Each wind turbine is a long tower with a large structure at the top. The structure at the top of each wind turbine consists of three long, curved blades that look like airplane wings. The blades of wind turbines are spinning at different speeds in the video.
The scene emphasizes how variations in rotational speed affect the generation of electrical energy. Since each turbine is connected to a

Student view

generator, their differing speeds would result in variations in the frequency of the induced emf. This concept is linked to how wind conditions and turbine efficiency impact electricity generation in a real-world power grid. The video illustrates the principle that a faster-spinning turbine produces a higher frequency output compared to a slower one.

What happens to the output emf when we increase the frequency of rotation? Take a look at the simulation in **Interactive 2**. What impact does changing the different variables have on the emf? Why?

Interactive 2. The Impact on the EMF Due to the Change in Different Variables.

More information for interactive 2

This interactive simulation demonstrates **electromagnetic induction** by illustrating how a changing magnetic field induces an electromotive force (EMF) in a rotating coil. The right-side graphs track two key quantities: **magnetic flux** and **EMF**, both plotted against time. The **x-axis represents time**, while the y-axes represent **magnetic flux** and **EMF, respectively**. As the coil rotates within the magnetic field, users can observe how these values change dynamically.

The interactive allows users to modify three important parameters: **frequency of rotation, magnetic field strength, and coil area**. The **frequency of rotation** determines how fast the coil spins within the field, directly affecting the rate of change of flux. The **magnetic field strength** influences the total flux passing through the coil, while the **coil area** determines how much of the field is intercepted by the coil. These parameters can be adjusted using the sliders at the bottom of the simulation.

As users increase the rotation frequency, they observe that both the magnetic flux and the induced EMF oscillate more rapidly. A stronger magnetic field or larger coil area results in greater flux changes, producing a stronger EMF. These relationships reflect the principles of Faraday’s Law, which explains how voltage is generated when there is a change in magnetic flux. The simulation dynamically updates the graphs, providing an intuitive representation of how AC voltage is generated.

In the image, the coil rotates at 2.8 rotations per second, causing sinusoidal oscillations in both magnetic flux and EMF. To use this interactive, users can adjust the sliders for the frequency of rotation, magnetic field strength, and coil area. After making adjustments, users can press "Play" to simulate the system's behavior. The graphs will display the resulting changes in magnetic flux and EMF as the coil rotates. Users can pause or reset the simulation to observe the effects of different parameter values on the graphs.

This interactive provides a hands-on way to explore how electromagnetic induction works and how different factors affect the induced EMF and magnetic flux. By adjusting the frequency of rotation, magnetic field strength, and coil area, users can better understand the relationships between these variables and how they contribute to the generation of electricity through electromagnetic induction. The graphs allow for a visual representation of the dynamic changes in the system, helping users grasp the fundamental principles of electromagnetic induction in a tangible way.

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Increasing the coil area or the magnetic field strength increases the emf because of the relationship derived in this section:

$$\varepsilon = -N\frac{\Delta BA\cos\theta}{\Delta t}$$

Since,

$$\Phi = BA\cos\theta$$

Increasing the number of turns in the coil would also increase the emf.

What happens if we increase the frequency of rotation? Increasing how fast the coil spins increases the frequency of the oscillations of the emf, but it also increases the magnitude of the emf because it increases the rate of change of magnetic flux (**Figure 7**).

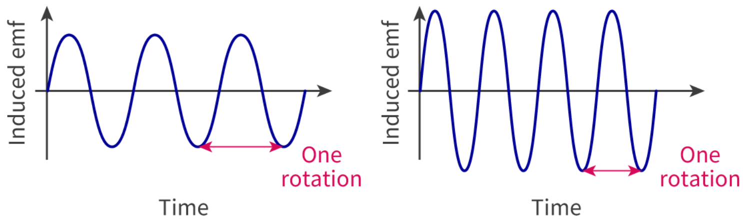

Figure 7. Graphs of induced emf against time.

More information for figure 7

The image consists of two line graphs side by side. Both graphs plot 'Induced emf' on the Y-axis against 'Time' on the X-axis. The graph on the left shows a sinusoidal wave with lower frequency, indicating slower oscillations. The distance for one complete rotation is greater. The graph on the right shows a similar sinusoidal wave but with a higher frequency, representing faster oscillations. The distance for one rotation is shorter compared to the left graph. The increase in the frequency of oscillations illustrates the effect of increasing the speed of rotation on the emf.

[Generated by AI]

Worked example 1

In a wind turbine, the motion of the turbine induces an emf, ϵ, in a coil of N turns and area A. The coil rotates inside a magnetic field of strength B. How could an engineer increase the induced emf without using more wire in the coil?

There are the four ways to increase the emf, and two of them involve using more wire: increasing N and increasing A.

It is unlikely that the engineer will be able to make the turbine spin faster because this depends on the speed of the wind and is not controllable.

The engineer's only option is to increase the strength of the magnetic field, B.

Another possible solution is to change two square turns of a coil of side length a to one larger square turn of side length $2a$ — the same length of wire is used. The area of the coil increases from a^2 to $4a^2$, but the number of coils, N, is reduced by 2. Does this mean the magnetic flux is increased?

Engineers are often faced with these challenges of increasing outputs while managing costs.

Work through the activity to check your understanding of AC generators.

Student
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Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:**
  - Communication skills — Reflecting on the needs of the audience when creating engaging presentations
  - Social skills — Assigning and accepting specific roles during group activities
- **Time required to complete activity:** 1 hour
- **Activity type:** Group activity

Look at **Video 2.** It attempts, with a few errors or omissions, to explain the theory behind an AC generator. Your task is to plan and produce a video without errors and with more creativity.

Video 2. Factors that affect a generated emf.

Job roles:

Think about the personal strengths of your group. Who is good at what? You might consider a director, actors or narrators, videographers or creatives.

Style of the video:

Think about how you want to present the information. Do you want to star in the video? Present using props? Or animation? Or something else?

Content:

Plan exactly what you want to say and how you are going to say it. List everything you need to get across in the video.

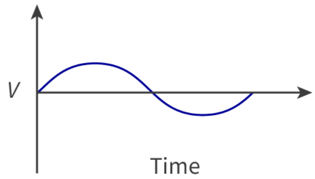
5 section questions

Question 1

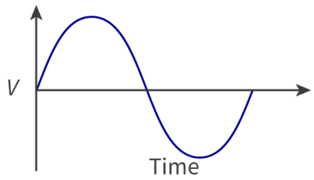
HL Difficulty:

Graph X shows potential difference generated, V, against time for an AC generator being turned at a speed v.

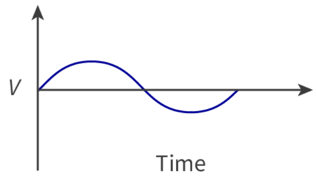
Student view



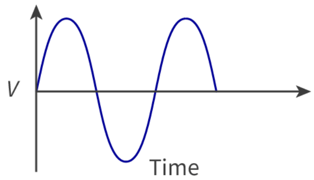
Graph X



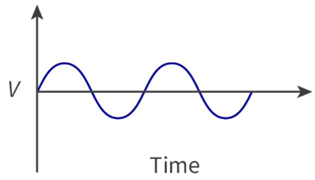
Graph M



Graph N



Graph O



Graph P

More information

Which graph (**M**, **N**, **O** or **P**) shows that the AC generator is being turned at a speed greater than *v*?

All the graphs are drawn to the same scale.

1 O ✓

2 M

3 N

4 P

Explanation

Increasing the frequency of rotation increases the frequency of the alternating emf **and** the magnitude, because it increases the rate of change of magnetic flux through the coil.

Question 2

HL Difficulty:

Which of these will have **no** effect on the magnitude of the emf produced by a rotating coil in a permanent magnetic field?

1 Reversing the direction of the magnetic field ✓

2 Increasing the number of turns in the coil

3 Decreasing the time period of the rotation

4 Increasing the radius of the coil

Explanation

Overview
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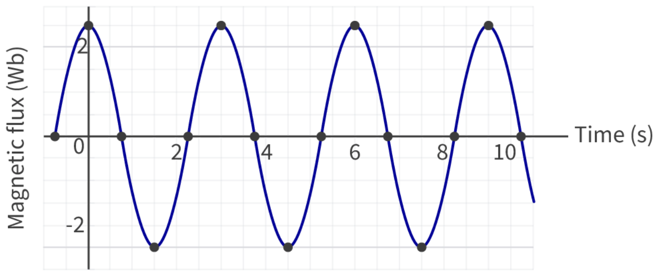
Reversing the direction of the magnetic field will reverse the direction of current flow in the coil at any given moment and will not affect the magnitude of the emf. All the others do affect the magnitude of the emf.

Question 3

HL Difficulty:

The graph shows the magnetic flux passing through a rotating coil.



More information

At time t = 2.5 s, what is the induced emf?

1 Negative, non-zero ✓

2 Positive, non-zero

3 Zero

4 It depends on the direction of rotation

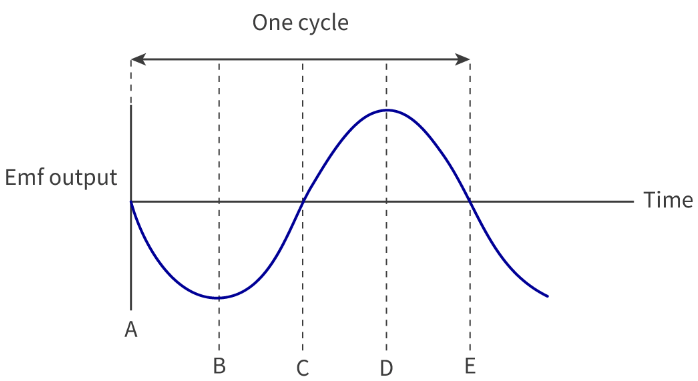
Explanation

The graph shows magnetic flux against time. The emf produced is the negative gradient of the graph, so at t = 2.5 s, the gradient is positive and non-zero, so the emf is negative and non-zero.

Question 4

HL Difficulty:

The graph shows the emf output of an AC generator with time.



More information

Student view

Overview
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At which point(s) is the magnitude of the magnetic flux through the coil at a maximum?

1 A, C or E ✓

2 B or D

3 Impossible to tell from the graph

4 A or E

Explanation

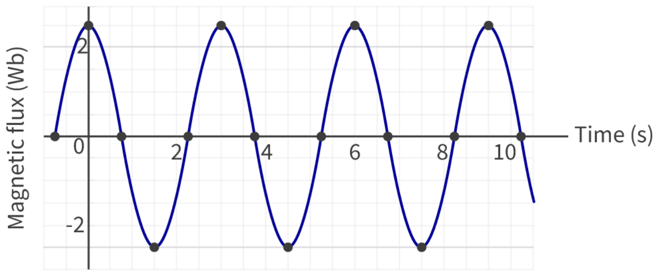
Magnetic flux is at a maximum when the plane of the coil is perpendicular to the magnetic field. At this point, the movement of the coil is parallel to the magnetic field. Therefore, there is no change in magnetic flux, so the emf generated is zero.

At A, C and E, the emf is zero so the coil is perpendicular to the magnetic field and the magnetic flux through the coil is at maximum.

Question 5

HL Difficulty:

The graph shows the magnetic flux passing through a rotating coil.



More information

The frequency of rotation is halved. At what time will the emf produced be zero?

1 3.0 s ✓

2 1.5 s

3 2.25 s

4 0.75 s

Explanation

The graph shows magnetic flux against time. The emf produced is the negative gradient of the graph, so at a peak or a trough, the gradient is 0, and there is 0 emf.

The frequency of rotation is halved, so the cycle takes twice as long to reach each point (doubling *t*). The first peak/trough is at *t* = 0. Doubling this gives *t* = 0. This is not an option. The second peak/trough is at *t* = 1.5 s. Doubling this gives *t* = 3.0 s, which is an option and the correct answer.

Student view

D. Fields / D.4 Induction (HL)

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Summary and key terms (HL)

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-hl-id-46427/print/) Assign

Higher level (HL)

- Magnetic fields can be described in terms of lines of magnetic flux, which can be calculated using $\Phi = BA\cos\theta$.
- The magnetic flux density of a magnetic field is equivalent to the magnetic field strength.
- A changing magnetic flux passing through a loop of a conductor induces an emf in that conductor, while an unchanging magnetic flux does not induce an emf.
- The induced emf can be calculated using:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \text{ and } \varepsilon = BvL$$

- Lenz's law states that a induced current will flow in such a way that it produces a magnetic field to oppose the change that caused it. This is a result of the principle of conservation of energy.
- Self-induction is a phenomenon in which the change in magnetic flux through a coil is produced by the change in magnetic field created by the coil itself, by changing the current flowing through it.
- The most useful way to continuously change the magnetic flux through a coil is by rotating the coil in a permanent magnetic field.
- Rotating a coil within a magnetic field induces a sinusoidal emf in the coil.
- Increasing the frequency of rotation of the coil increases the magnitude and frequency of the induced emf.

Student view

Overview
(/study/ap
aa-
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762593/c

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. The area of space where a magnetic pole experiences a force is called a .
2. The is the total number of magnetic field lines, whereas the number of magr field lines passing through a unit area is the magnetic .
3. is the production of an emf or current in a conductor due to a change in magnetic flux.
4. states that the direction of an induced current is such that it creates a magne field to oppose the change that caused it.
5. Most of the electricity in the world is generated by a coil in a magnetic field, which produces an current.
6. The phenomenon in which changing the current flowing through a coil induces an emf in the coil itself is called .
7. If the that a coil rotates in a magnetic field is increased, the and frequency of the induced emf is increased.

Induction | alternating | Lenz's law | magnetic field | frequency | self induction | rotating | flux density | magnitude | magnetic flux

Check

Interactive 1. Key Terms Related to Magnetism.

D. Fields / D.4 Induction (HL)

Checklist (HL)

Section | Student... (0/0) | Feedback | Print (/study/app/math-aa-hl/sid-423-cid-762593/book/checklist-hl-id-46428/print/) | Assign

Higher level (HL)

What you should know

After studying this subtopic, you should be able to:

- Understand the terminology used when describing fields interacting with conducting wires.
- Identify the variables that can change the amount of magnetic flux penetrating a loop.

Student
view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

- Use the equation for magnetic flux:

$$\Phi = BA\cos\theta$$

- Describe and explain the effect of a changing magnetic field on the emf in a conductor in that field.
- Calculate the induced emf in a conductor using:

$\varepsilon = -N\dfrac{\Delta\Phi}{\Delta t}$ and $\varepsilon = BvL$

- Understand the minus sign in the equation for induced emf:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$$

- Explain the direction of induced current with reference to conservation of energy.
- Explain the sinusoidal shape of magnetic flux and emf against time graphs for a coil rotating in a constant magnetic field.
- Identify and explain the changes in induced emf when the frequency of rotation changes in a constant magnetic field.

D. Fields / D.4 Induction (HL)

Investigation (HL)

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-hl-id-46429/print/) Assign

Higher level (HL)

- **IB learner profile attribute:** Communicator
- **Approaches to learning:** Communication skills — Reflecting on the needs of the audience when creating engaging presentations
- **Time required to complete activity:** 90 minutes
- **Activity type:** Group activity

Electrical energy is used globally as a versatile and easily transportable form of energy. But how we generate electricity varies from country to country.

We can generate electricity by rotating a coil in a magnetic field. There are many different ways to turn the coil.

Your task

Create a *Dragon's Den* or *Shark Tank* style pitch to potential investors for a product that harnesses a feature of your country or local area to produce electricity.

Practical skills

Inquiry 1: Exploring and designing — Designing

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

When designing or engineering a product, engineers and scientists go through many stages. One design thinking framework has five stages that are repeated in a cycle:

1. Empathise: Try to understand the needs of the community. Research the current situation and how the community views challenges.
2. Define: Use the research to clearly define a problem you will try to solve.
3. Ideate: Come up with as many ideas as you can that could potentially solve the problem. The more creative and imaginative the better.
4. Prototype: Build, or make plans to build, some of your best ideas.
5. Test: Show your prototype(s) to others to see what they think, and get their feedback. Go back to Step 1, empathise with what they are saying and refine your design.

You may choose to use this framework to approach this investigation.

Things you might want to consider

- What features of your country could be used? What forms of energy do they represent?
- Explain to investors how electricity is generated by your device.
- Explore the history of electricity and the economic benefits of electricity over time.
- Give details on the sustainability and environmental impact of your device. How much material will you use? How will you maximise induced emf?
- Explain to investors why it is so important that they invest in your product.

Resources you could use

- History of electricity generation:Wikipedia.org/wiki/Electricity_generation (https://en.wikipedia.org/wiki/Electricity_generation#:~:text=The%20fundamental%20principles%20of%20electricity,the
- Current methods of electricity production: https://ourworldindata.org/grapher/share-elec-by-source (https://ourworldindata.org/grapher/share-elec-by-source)

Identify the current methods of production in your country and globally.

- Renewable energy resource maps: https://www.esmap.org/re_mapping (https://www.esmap.org/re_mapping)
- UN sustainable development goals: https://sdgs.un.org/goals (https://sdgs.un.org/goals)

Consider which of these goals would be supported by increased access to electricity.

- The resources in all the sections of subtopic D.4 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-46422/)
- Physical prototypes, or digital prototypes made using resources such as Tinkercad: https://www.tinkercad.com/ (https://www.tinkercad.com/)

How you could assess this work

Each team or individual delivers their pitch to the whole class. Everyone in the class has a million dollars they can invest in one or more innovations (not including their own). The team or person with the most invested money at the end wins!

Student view

Reflection (HL)

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

HL Extension

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-46422/).

- What are the effects of relative motion between a conductor and a magnetic field?
- How can the power output of electrical generators be increased?
- How did the discovery of electromagnetic induction affect industrialisation?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic D.4 Induction (HL)

Help us improve the content and user experience.