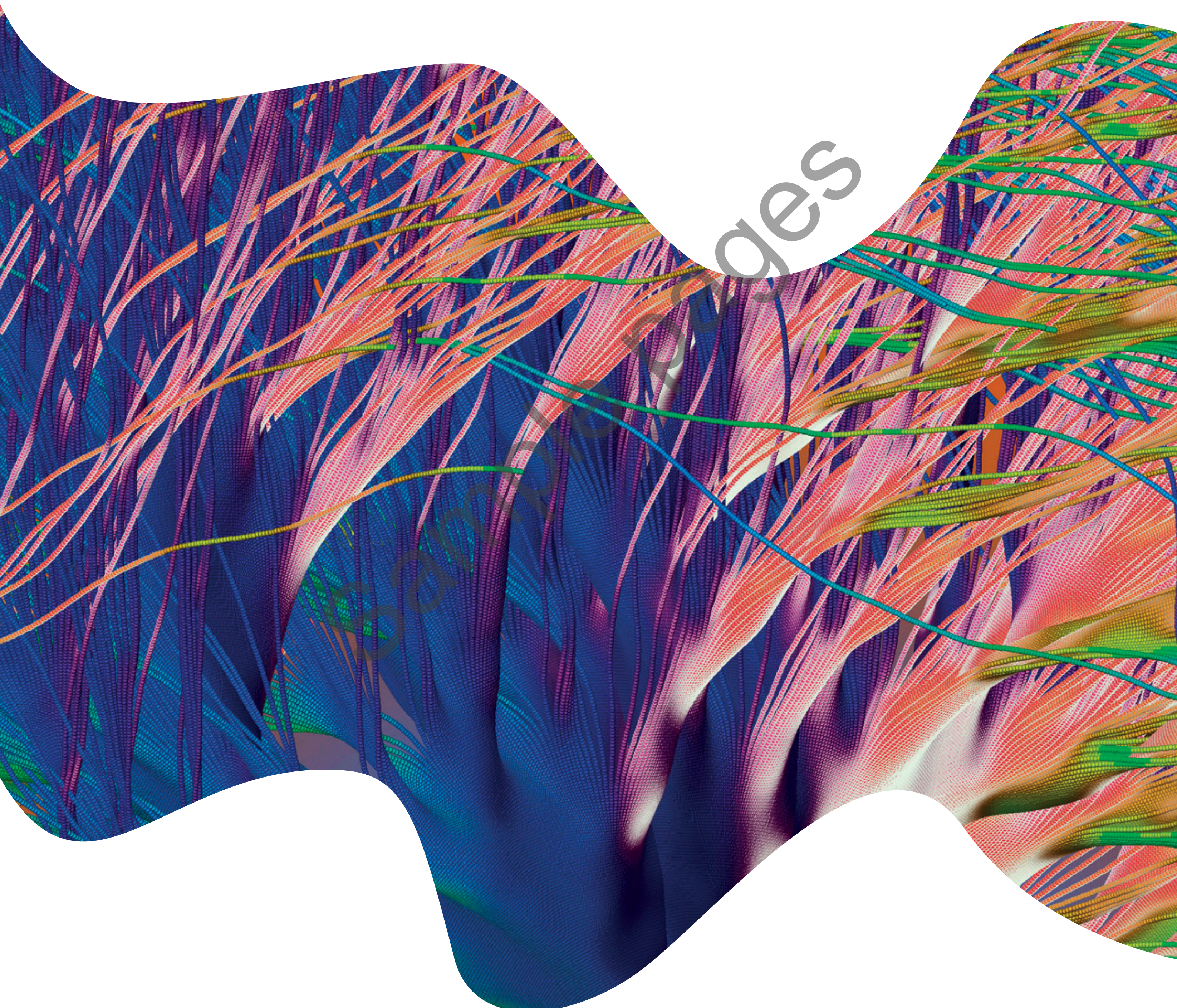
PEARSON

PHYSICS 12

NEW SOUTH WALES

STUDENT BOOK



NSW
STAGE 6

PEARSON
PHYSICS
NEW SOUTH WALES

12

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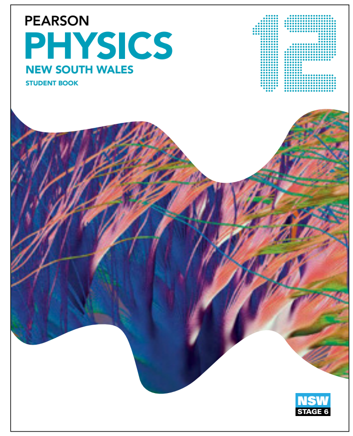

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Contents

Module 8 From the universe to the atom

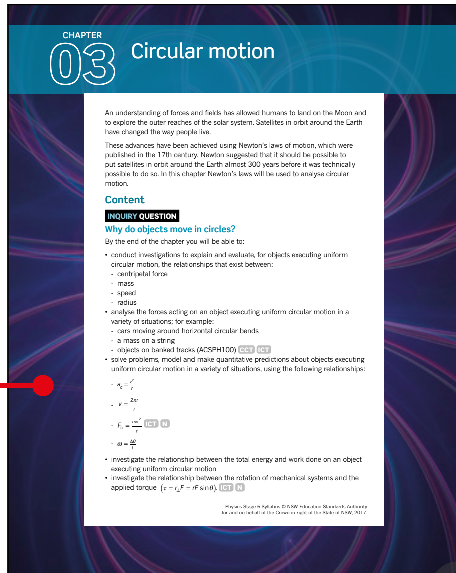
How to use this book

Pearson Physics 12 New South Wales

Pearson Physics 12 New South Wales has been written to be fully aligned with the new Stage 6 syllabus for New South Wales Physics. The book covers Modules 5 to 8 in an easy-to-use resource. Explore how to use this book below.

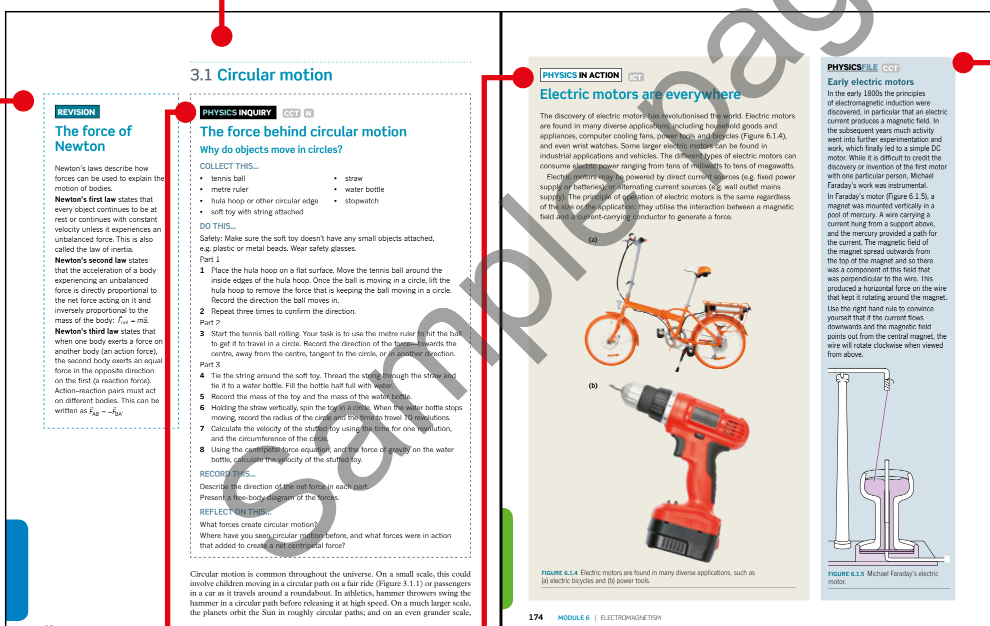
Chapter opener

The chapter opening page links the syllabus to the chapter content. Key content addressed in the chapter is clearly listed.



Section

Each chapter is clearly divided into manageable sections of work. Best-practice literacy and instructional design are combined with high-quality, relevant photos and illustrations to help students better understand the idea or concept being developed.



PhysicsFile

PhysicsFile boxes include a range of interesting and real-world examples to engage students.

Revision box

Revision boxes are used to remind students of vital concepts previously covered that are required for current learning.

Physics Inquiry

Physics Inquiry features are inquiry-based activities that assist students to discover concepts before learning about them. They encourage students to think about what happens in the world and how science can provide explanations.

Physics in Action

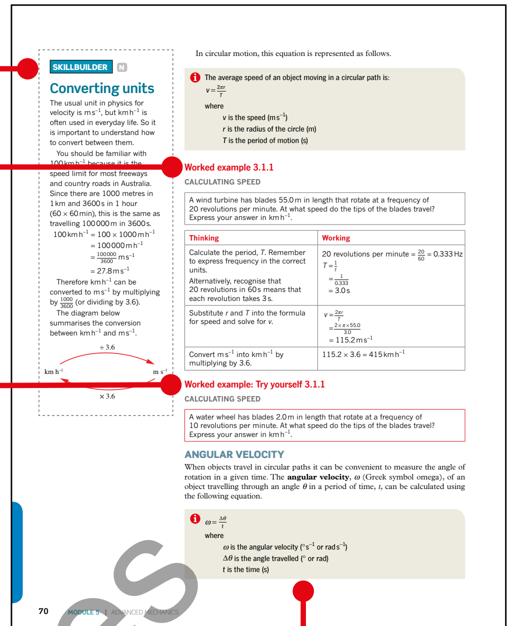
Physics in Action boxes place physics in an applied situation or a relevant context. They refer to the nature and practice of physics, its applications and associated issues, and the historical development of its concepts and ideas.

SkillBuilder

A SkillBuilder outlines a method or technique. They are instructive and self-contained. They step students through the skill to support science application.

Worked examples

Worked examples are set out in steps that show thinking and working. This format greatly enhances student understanding by clearly linking underlying logic to the relevant calculations. Each Worked example is followed by a Try yourself activity. This mirror problem allows students to immediately test their understanding.

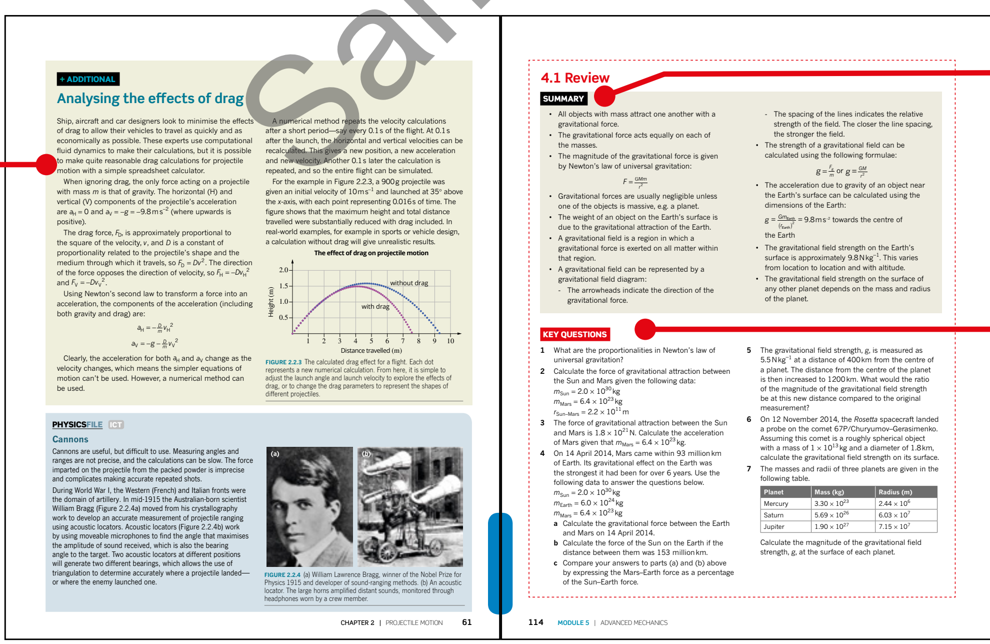


Highlight box

Highlight boxes focus students' attention on important information such as key definitions, formulae and summary points.

Additional content

Additional content includes material that goes beyond the core content of the syllabus. They are intended for students who wish to expand their depth of understanding in a particular area.



Section summary

Each section has a summary to help students consolidate the key points and concepts.

Section review questions

Each section finishes with key questions to test students' understanding of and ability to recall the key concepts of the section.

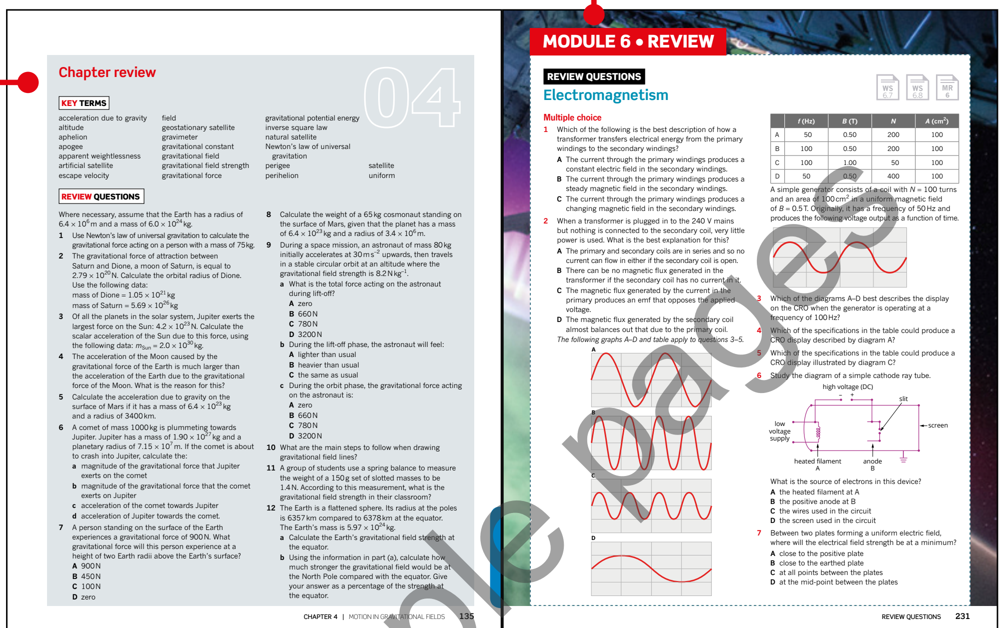
How to use this book

Chapter review

Each chapter finishes with a list of key terms covered in the chapter and a set of questions to test students' ability to apply the knowledge gained from the chapter.

Module review

Each module finishes with a set of questions, including multiple choice and short answer. These assist students in drawing together their knowledge and understanding, and applying it to these types of questions.



Icons

The NSW Stage 6 syllabus 'Learning across the curriculum' and 'General capabilities' content are addressed throughout the series and are identified using the following icons.

AHC A CC CCT DD EU ICT

IU L N PSC S WE

'Go to' icons are used to make important links to relevant content within the same Student Book.

GO TO ➤

This icon indicates when it is the best time to engage with a worksheet (WS), a practical activity (PA), a depth study (DS) or module review (MR) questions in *Pearson Physics 12 New South Wales Skills and Assessment* book.

WS 3.1

This icon indicates the best time to engage with a practical activity on *Pearson Physics 12 New South Wales* Reader+.

PA 3.1

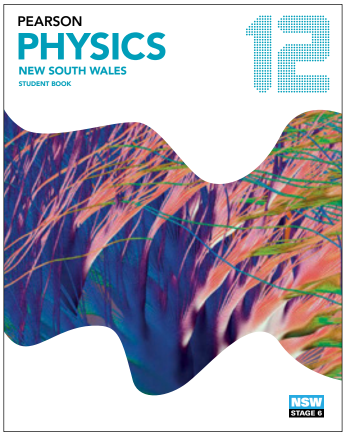
Glossary

Key terms are shown in **bold** in sections and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all the key terms.

Answers

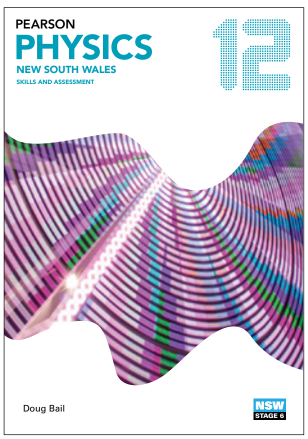
Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, Worked example: Try yourself features, chapter review questions and module review questions are provided on *Pearson Physics 12 New South Wales* Reader+.

Pearson Physics 12
New South Wales



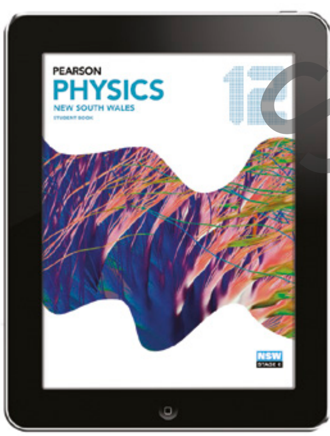
Student Book

Pearson Physics 12 New South Wales has been written to fully align with the new Stage 6 syllabus for New South Wales. The Student Book includes the very latest developments in and applications of physics and incorporates best-practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.



Skills and Assessment Book

Pearson Physics 12 New South Wales Skills and Assessment book gives students the edge in preparing for all forms of assessment. Key features include a toolkit, key knowledge summaries, worksheets, practical activities, suggested depth studies and module review questions. It provides guidance, assessment practice and opportunities for developing key skills.



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Pearson Reader+ lets you use your Student Book online or offline on any device. Pearson Reader+ retains the look and integrity of the printed book. Practical activities, interactives and videos are available on Pearson Reader+, along with fully worked solutions for the Student Book questions.

Teacher Support

Online teacher support for the series includes syllabus grids, a scope and sequence plan, and three practice exams per year level. Fully worked solutions to all Student Book questions are provided, as well as teacher notes for the chapter inquiry tasks. Skills and Assessment book resources include solutions to all worksheets, practical activities, depth studies and module review questions; teacher notes, safety notes, risk assessments and lab technician's checklists and recipes for all practical activities; and assessment rubrics and exemplar answers for the depth studies.

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CHAPTER 07

Electromagnetic induction

In 1831, Englishman Michael Faraday and American Joseph Henry independently discovered that a changing magnetic flux could induce an electric current in a conductor. This discovery made possible the production of vast quantities of electricity. Today, whether the primary energy source is burning coal, wind, nuclear fission or falling water, most of the world's electrical energy production is the result of electromagnetic induction.

Content

INQUIRY QUESTION

How are electric and magnetic fields related?

By the end of this chapter you will be able to:

- describe how magnetic flux can change, with reference to the relationship $\Phi = B_{\parallel}A = BA\cos\theta$ (ACSPH083, ACSPH107, ACSPH109) ICT N
- analyse qualitatively and quantitatively, with reference to energy transfers and transformations, examples of Faraday's law and Lenz's law $\left(\varepsilon = -N\frac{\Delta\Phi}{\Delta t}\right)$, including but not limited to: (ACSPH081, ACSPH110) ICT N
  - the generation of an electromotive force (emf) and evidence for Lenz's law produced by the relative movement between a magnet, straight conductors, metal plates and solenoids
  - the generation of an emf produced by the relative movement or changes in current in one solenoid in the vicinity of another solenoid
- analyse quantitatively the operation of ideal transformers through the application of: (ACSPH110) ICT N
  - $\frac{V_P}{V_S} = \frac{N_P}{N_S}$
  - $V_P I_P = V_S I_S$
- evaluate qualitatively the limitations of the ideal transformer model and the strategies used to improve transformer efficiency, including but not limited to:
  - incomplete flux linkage
  - resistive heat production and eddy currents
- analyse applications of step-up and step-down transformers, including but not limited to:
  - the distribution of energy using high-voltage transmission lines. CCT

7.1 Magnetic flux

After Hans Christian Ørsted's discovery that an electric current produces a magnetic field, Michael Faraday, an English scientist, was convinced that the reverse should also be true—a magnetic field should be able to produce an electric current.

Faraday wound two coils of wire onto an iron ring (Figure 7.1.1). He connected a battery to one of the coils to create a strong current through it, which therefore created a strong magnetic field. He expected to then detect the creation of an electric current in the second coil. No matter how strong the magnetic field, he could not detect an electric current in the other coil.

One day he noticed that the galvanometer (a type of sensitive ammeter) attached to the second coil flickered when he turned on the current that created the magnetic field. It gave another flicker, in the opposite direction, when he turned the current off. It was not the strength of the magnetic field that mattered, but the change in the magnetic field.

The creation of an electric current in a conductor due to a change in the magnetic field acting on that conductor is now called **electromagnetic induction**.

FIGURE 7.1.1 Michael Faraday's original induction coil. Passing a current through one coil induces a voltage in the second coil by a process called mutual inductance. This coil is now on display at the Royal Institution in London.

PHYSICSFILE ICT

Models and theories

Michael Faraday was not alone in the discovery of electromagnetic induction. Joseph Henry (1797–1878), an American physicist, independently discovered the phenomenon of electromagnetic induction a little ahead of Michael Faraday, but Faraday was the first to publish his results. Henry later improved the design of the electromagnet, using a soft iron core wrapped in many turns of wire. He also designed the first reciprocating electric motor. Henry is credited with first discovering the phenomenon of self-induction, and the unit of inductance is named after him. He also introduced the electric relay, which made the sending of telegrams possible. Henry was the first director of the Smithsonian Institution.

While Faraday will be largely referred to throughout this text, it is worth noting that there can be a number of contributors who together built on the understanding of key ideas. Joseph Henry's contributions should not be forgotten.

CREATING AN ELECTRIC CURRENT

In his attempts to produce an electric current from a magnetic field, Faraday had no success with a constant magnetic field but was able to observe the creation of an electric current whenever there was a change in the magnetic field. This current is produced by an induced emf, ε. Although the term **emf** is derived from the name electromotive force, it is a voltage, or potential difference, rather than a force. Figure 7.1.2 indicates the induction of emf, and therefore current, caused by the perpendicular movement of a conducting wire relative to a magnetic field.

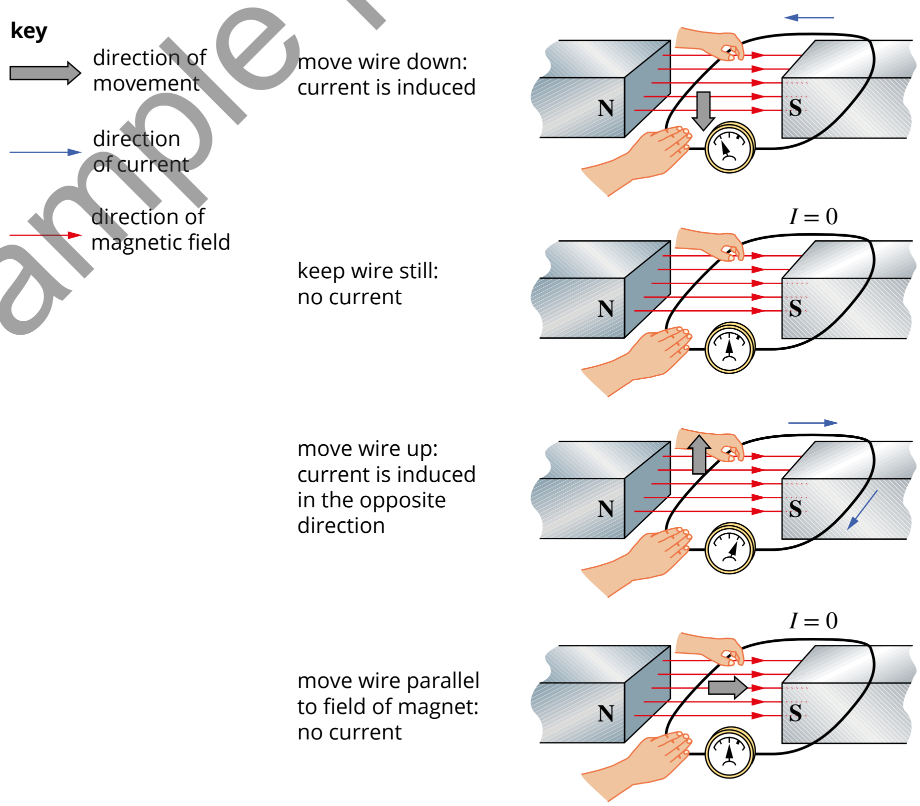


FIGURE 7.1.2 An electromotive force (emf) is induced in a wire when it moves perpendicular to a magnetic field.

MAGNETIC FLUX

To be able to develop ideas about the change in a magnetic field that induces an emf which can then create (or induce) a current, it is useful to be able to describe the 'amount of magnetic field'. This amount of magnetic field is referred to as the **magnetic flux**, a scalar quantity, denoted by the symbol Φ (the Greek letter phi). Faraday pictured a magnetic field as consisting of many lines of force. The density of the lines represents the strength of the magnetic field. Magnetic flux can be related to the total number of these lines that pass within a particular area. A strong magnetic field acting over a small area can produce the same amount of magnetic flux as a weaker field acting over a larger area, as shown in Figure 7.1.3. For this reason, magnetic field strength, B, is also referred to as **magnetic flux density**. B can be thought of as being proportional to the number of magnetic field lines per unit area perpendicular to the magnetic field.

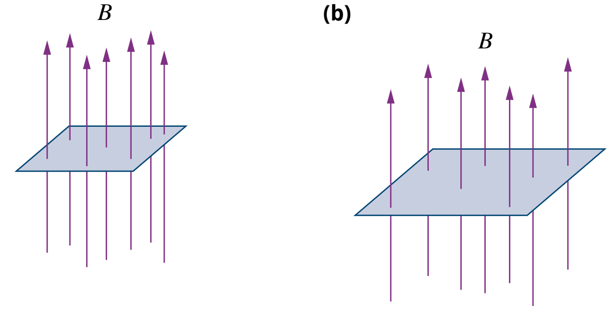


FIGURE 7.1.3 Magnetic flux: (a) a strong magnetic field acting over a small area (b) will have the same magnetic flux as a weaker magnetic field acting over a larger area.

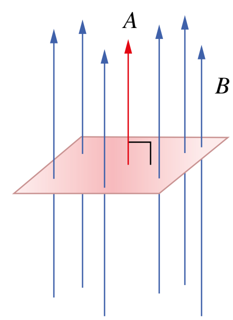


FIGURE 7.1.4 The area vector A (shown in red) is pointed in a direction normal to the plane of the area.

The area variable is actually represented by a vector A, the magnitude of which is equal to the area being examined. The direction of the area vector is normal to the plane of the area. This is shown in Figure 7.1.4.

The magnetic flux will be at a maximum when the area vector is parallel to the magnetic field, and zero when the area vector is perpendicular to the magnetic field.

Based on this, magnetic flux is defined as the product of the strength of the magnetic field, B, and the area of the field, i.e.

$$\Phi = B_{\parallel} A$$

where

Φ is the magnetic flux. The unit for magnetic flux is the weber, abbreviated to Wb, where 1 Wb = 1 T m^{-2}

$B_{\parallel}$ is the strength of the magnetic field parallel to the area vector (T)

A is the area vector (m^2)

Since it is the plane of the area perpendicular to the magnetic field, the angle between the magnetic field and the area through which the field passes will affect the amount of magnetic flux. As the angle changes, the amount of magnetic flux will also change, until it reaches zero when the area under consideration is parallel to the magnetic field. Referring to Figure 7.1.5, then the relationship between the amount of magnetic flux and the angle θ to the field is:

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

It is important to note that θ is not the angle between the plane of the area and the magnetic field. Rather, it is the angle between a normal to the area and the direction of the magnetic field; hence the use of cos θ. When the area is at right angles to the magnetic field, the angle θ between the normal and the field is 0° and cos 0 = 1 (top diagram in Figure 7.1.5). When the area is parallel to the magnetic field, the angle θ between the normal and the field is 90° and cos 90 = 0 (bottom diagram in Figure 7.1.5).

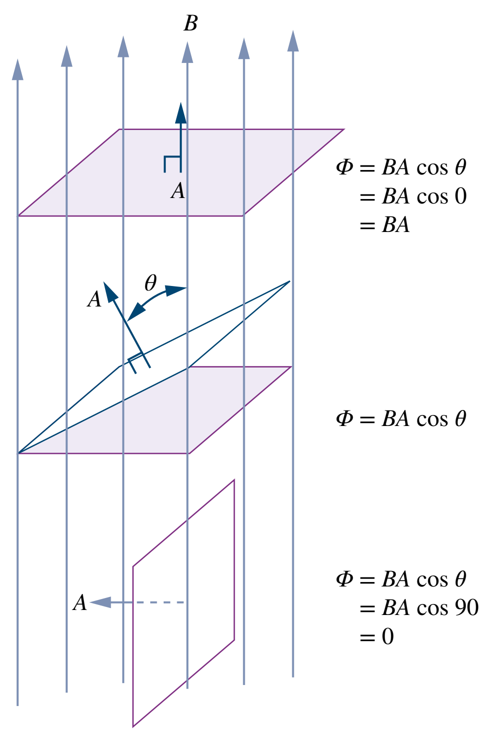


FIGURE 7.1.5 The magnetic flux is the strength of the magnetic field, B, multiplied by the area perpendicular to the magnetic field, given by $A \cos\theta$ and shown as the shaded areas in the above diagrams.

Worked example 7.1.1

MAGNETIC FLUX

A student places a horizontal square coil of wire of side length 5.0 cm into a uniform vertical magnetic field of 0.10 T. How much magnetic flux ‘threads’ the coil?

Thinking	Working
Calculate the area of the coil perpendicular to the magnetic field.	side length = 5.0 cm = 0.05 m area of the square = $(0.05\,\text{m})^2$ = $0.0025\,\text{m}^2$
Calculate the magnetic flux.	$\Phi = B_{\parallel}A$ $= 0.1 \times 0.0025$ $= 0.00025$ Wb
State the answer in an appropriate form.	$\Phi = 2.5 \times 10^{-4}$ Wb or 0.25 mWb

Worked example: Try yourself 7.1.1

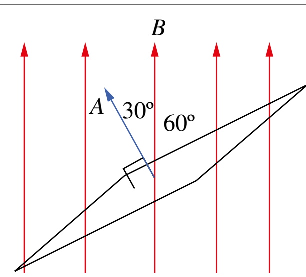
MAGNETIC FLUX

A student places a horizontal square coil of wire of side length 4.0 cm into a uniform vertical magnetic field of 0.050 T. How much magnetic flux ‘threads’ the coil?

Worked example 7.1.2

MAGNETIC FLUX AT AN ANGLE

A student places a square coil of wire of side length 10.0 cm into a uniform vertical magnetic field of 0.20 T. The plane of the square coil is at an angle of 60° to the magnetic field. How much magnetic flux ‘threads’ the coil?

Thinking	Working
Calculate the area of the coil.	side length = 10.0 cm = 0.1 m area of the square = $(0.01\,\text{m})^2$ = $0.01\,\text{m}^2$
Draw a diagram to calculate the angle θ.	 The plane of the area is 60° to the magnetic field. So the area vector, which is directed normal to the plane, will be at an angle: $\theta = 90 - 60$ $= 30°$
Calculate the magnetic flux.	$\Phi = BA \cos\theta$ $= 0.2 \times 0.01 \times \cos 30$ $= 0.0017$ Wb
State the answer in an appropriate form.	$\Phi = 1.7 \times 10^{-3}$ Wb or 1.7 mWb

Worked example: Try yourself 7.1.2

MAGNETIC FLUX AT AN ANGLE

A student places a square coil of wire of side length 5.0 cm into a uniform vertical magnetic field of 0.10 T. The plane of the square coil is at an angle of 40° to the magnetic field. How much magnetic flux 'threads' the coil?

Note that in Worked Example 7.1.1 an area of 5 cm × 5 cm = 25 cm^2 was considered, and this corresponds to 0.0025 m^2 or 25 × 10^{-4} m^2; in other words:

$1\,\text{cm}^2 = 1 \times 10^{-4}\,\text{m}^2$

THE INDUCED EMF IN A MOVING CONDUCTOR

It was discovered that a change in the magnetic field, when a magnet is moved closer to a conductor, leads to an induced emf that in turn produces an **induced current**. While Faraday largely based his investigations on induced currents in coils, another way of inducing an emf is by moving a straight conductor in a magnetic field. It's not hard to understand why this is the case, when you know that charges moving in a magnetic field will experience a force.

Recall that when a charge, q, moves at a velocity v, perpendicular to a magnetic field B, the charge experiences a force F equal to $qv_{\perp}B$.

Considering the direction of movement shown in Figure 7.1.6, the force on the positive charges within the moving conductor would be along the conductor and out of the page. The force on the negative charges within the conductor would be along the conductor but into the page.

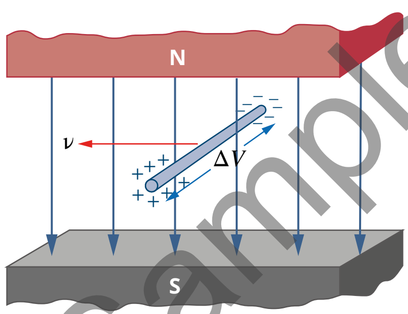


FIGURE 7.1.6 A potential difference, ΔV, will be produced across a straight wire moving to the left in a downward-pointing magnetic field.

As the charges in Figure 7.1.6 move apart due to the force they are experiencing from the magnetic field, one end of the conductor will become more positive, the other will become more negative, and a potential difference, ΔV, or emf will be induced between the ends of the conductor.

7.1 Review

SUMMARY

- An induced emf, ε, is produced by a changing magnetic flux in a process called electromagnetic induction.
- Magnetic flux is defined as the product of the strength of the magnetic field, B, and plane of the area perpendicular to the field lines, i.e. $\Phi = B_{\parallel}A$.
- The amount of magnetic flux varies with the angle of the field to the area under investigation; i.e. $\Phi = BA\cos\theta$. The angle θ is defined as between the magnetic field and the area vector which is directed normal to the plane of the area. The magnetic flux is then a maximum when the area vector is parallel (0°) and zero when the area vector is perpendicular (90°) to the field.
- The unit for magnetic flux is the weber, Wb; $1\,\text{Wb} = 1\,\text{T}\,\text{m}^{-2}$.

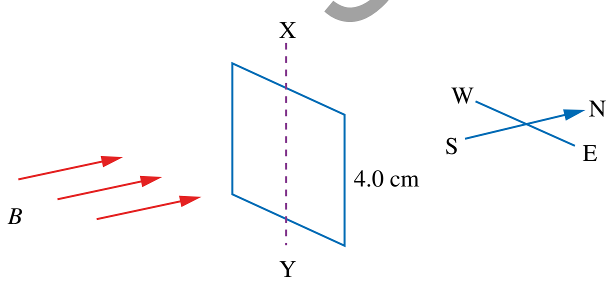
KEY QUESTIONS

1 Which of the following scenarios will *not* induce an emf in a long, straight conductor?

A A magnet is stationary alongside the conductor.
B A magnet is brought near the conductor.
C The conductor is brought into a magnetic field.
D The conductor is rotated within a magnetic field.

2 A student places a 4.0 cm square coil of wire parallel to a uniform vertical magnetic field of 0.050 T. How much magnetic flux 'threads' the coil?

3 A square loop of wire, of side 4.0 cm, is in a region of uniform magnetic field, $B = 2.0 \times 10^{-3}$ T north, as in the diagram below. The loop is free to rotate about a vertical axis XY. When the loop is in its initial position, its plane is perpendicular to the direction of the magnetic field. What is the magnetic flux passing through the loop?



4 The same square loop of wire as in Question 3 is initially perpendicular to the magnetic field. The loop is free to rotate about a vertical axis XY. Describe what happens to the amount of magnetic flux passing through the loop as the loop is rotated through one complete revolution.

5 A circular coil of wire, of radius 5.0 cm, is perpendicular to a region of uniform magnetic field, $B = 1.6$ mT. What is the magnetic flux passing through the loop?

6 Calculate the magnetic flux through a horizontal square coil of wire of side length 5.0 cm perpendicular to a uniform vertical magnetic field of 0.10 T.

7 Calculate the magnetic flux through a circular coil of wire of radius 3.0 cm. The plane of the coil is at an angle of 50° to the magnetic field of strength 2.5 mT.

7.2 Faraday's and Lenz's laws

PHYSICS INQUIRY N CCT

Electromagnetic induction

How are electric and magnetic fields related?

COLLECT THIS...

- cylindrical rare-earth magnet, longer than the diameter of the tube so that it cannot spin inside the tube
- plastic tubing with an internal diameter large enough for the magnet to fall freely
- a spool of enamel copper wire
- two LEDs, 10mm, at least 5000 mcd, different colours
- soft landing material (pillow, fabric, Styrofoam)

DO THIS...

1. Wind the copper wire around the tubing, creating a 3 cm length of tube with hundreds of loops of wire.
2. Connect the LEDs to the two ends of the wire. Place the LEDs in different orientations. Ensure a good electrical connection by sanding the enamel off the wire. If possible solder the wire and LED legs together.
3. Place the tubing over the soft landing material. Drop the magnet through the tube.

RECORD THIS...

Describe how the energy is transferred and transformed during this activity.

Present a top-view diagram of the tubing, indicating the magnetic flux as the magnet enters the wire section and the direction of the induced current. Draw a similar diagram as the magnet is in the centre of the wire section and when it leaves the wire section.

REFLECT ON THIS...

How are electric and magnetic fields related?

What variables affect the current produced?

Faraday's early experiments largely centred on investigating electromagnetic induction in coils, or multiple loops, of wire. Faraday found that if a magnet is quickly moved into a coil, an emf is induced which causes a current to flow in the coil. If the magnet is removed, then a current flows in the coil in the opposite direction. Alternatively, if the magnet is held steady and the coil is moved in such a way that changes the magnetic flux, then once again an emf is induced and an electric current flows. It doesn't matter whether the coil or the magnet is moved—it is a *change* in flux that is required to induce the emf (Figure 7.2.1). This discovery led Faraday to his law of induction. Faraday's law of induction is the focus of this section.

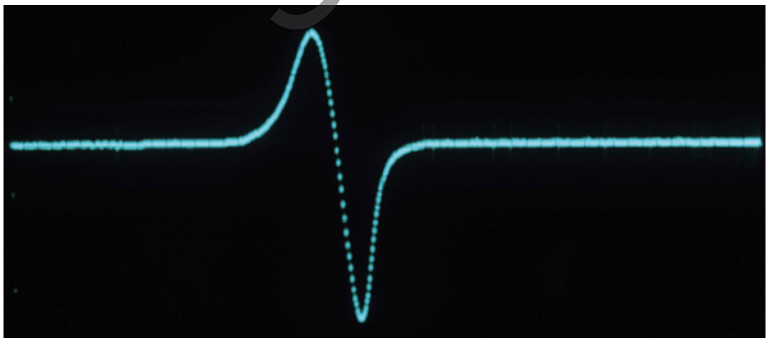


FIGURE 7.2.1 Oscilloscope trace from an electric coil, showing the voltage across the coil as a magnet is dropped through it.

FACTORS AFFECTING INDUCED EMF

Faraday quantitatively investigated the factors affecting the size of the emf induced in a coil. Firstly, emf will be induced by a change in the magnetic field. A simple example of this is to witness the emf induced when a magnet is brought towards or away from a wire coil. The greater the change, the greater the emf.

However, it is not only a change in the strength of a magnetic field, B, that induces an emf. It was noticed that an emf can be induced by changing the area perpendicular to the magnetic field through which the magnetic field lines pass, while keeping B constant. An example of this is the emf induced when a wire coil is rotated in the presence of a fixed magnetic field. This discovery indicates that the requirement for an induced emf is to have a changing magnetic flux, Φ.

Finally, Faraday discovered that the faster the change in magnetic flux, the greater the induced emf. This can be seen in the oscilloscope trace of a magnet falling through a coil as shown in the Figure 7.2.1 on page 189. The magnet is accelerated by gravity as it drops through the coil. Hence, the peak emf induced when the magnet first enters the coil at a relatively lower speed is noticeably less than the peak emf induced when the magnet leaves the coil at a faster speed. Thus, it is the *rate of change* of magnetic flux that determines the induced emf.

FARADAY'S LAW OF INDUCTION

Faraday's investigations led him to conclude that the average emf induced in a conducting loop, in which there is a changing magnetic flux, is proportional to the rate of change of flux.

This is now known as **Faraday's law** of induction and is one of the basic laws of electromagnetism.

Magnetic flux is defined as $\Phi = B_{\parallel}A$.

If the flux through N turns (or loops) of a coil changes from Φ_1 to Φ_2 during a time t, then the average induced emf during this time will be:

$$\varepsilon = -N\frac{(\Phi_2 - \Phi_1)}{t}$$

and if the change in magnetic flux $\Phi_2 - \Phi_1 = \Delta\Phi$, then

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

The negative sign is placed there as a reminder of the direction of the induced emf. This is discussed further on in the section. Normally you will be concerned only with the magnitude of the emf, which means you don't consider the negative sign or any negative quantities in a calculation.

If the ends of the coil are connected to an external circuit, then a current, I, will flow. The magnitude of the current is found using Ohm's law, which is:

$$I = \frac{V}{R}$$

where R is the resistance and V is the emf of the coil.

A coil not connected to a circuit will act like a battery not connected to a circuit. There will still be an induced emf but no current will flow.

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

where

- ε is the induced emf (V)
- N is the number of turns or loops
- $\Delta\Phi$ is the change in magnetic flux (Wb)
- Δt is the change in time (s)

Worked example 7.2.1

INDUCED EMF IN A COIL

A student winds a coil of area 40 cm^2 with 20 turns. He places it horizontally in a vertical uniform magnetic field of 0.10 T.

a Calculate the magnetic flux perpendicular to the coil.	
Thinking	**Working**
Identify the quantities to calculate the magnetic flux through the coil and convert to SI units where required.	$\Phi = B_{\parallel}A$ $B = 0.10$ T $A = 40\text{ cm}^2 = 40 \times 10^{-4}\text{ m}^2$
Calculate the magnetic flux and give your answer with appropriate units.	$\Phi = B_{\parallel}A$ $= 0.10 \times 40 \times 10^{-4}$ $= 4.0 \times 10^{-4}$ Wb

b Calculate the magnitude of the average induced emf in the coil when the coil is removed from the magnetic field in a time of 0.5 s.	
Identify the quantities needed to determine the induced emf. Ignore the negative sign.	$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$ $N = 20$ turns $\Delta\Phi = \Phi_2 - \Phi_1$ $= 0 - 4.0 \times 10^{-4}$ $= 4.0 \times 10^{-4}$ Wb $\Delta t = 0.5$ s
Calculate the magnitude of the average induced emf, ignoring the negative sign that indicates the direction.	$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$ $= 20 \times \frac{4.0\times10^{-4}}{0.5}$ $= 0.016 = 16$ mV

Worked example: Try yourself 7.2.1

INDUCED EMF IN A COIL

A student winds a coil of area 50 cm^2 with 10 turns. She places it horizontally in a vertical uniform magnetic field of 0.10 T.

a Calculate the magnetic flux perpendicular to the coil.

b Calculate the magnitude of the average induced emf in the coil when the coil is removed from the magnetic field in a time of 1.0 s.

Worked example 7.2.2

NUMBER OF TURNS IN A COIL

A coil of cross-sectional area 1.0×10^{-3} m^2 experiences a change in the strength of a magnetic field from 0 to 0.20 T over 0.50 s. If the magnitude of the average induced emf is measured as 0.10 V, how many turns must be on the coil?

Thinking	Working
Identify the quantities needed to calculate the magnetic flux through the coil when in the presence of the magnetic field and convert to SI units where required.	$\Phi = B_{\parallel}A$ $B = 0.20$ T $A = 1.0 \times 10^{-3}$ m^2
Calculate the magnetic flux when in the presence of the magnetic field.	$\Phi = B_{\parallel}A$ $= 0.20 \times 1.0 \times 10^{-3}$ $= 2.0 \times 10^{-4}$ Wb
Identify the quantities needed to determine the induced emf. Ignore the negative sign.	$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$ $N = ?$ $\Delta\Phi = \Phi_2 - \Phi_1$ $= 2.0 \times 10^{-4} - 0$ $= 2.0 \times 10^{-4}$ Wb $\Delta t = 0.50$ s $\varepsilon = 0.10$ V
Rearrange Faraday's law and solve for the number of turns on the coil. Ignore the negative sign.	$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$ $N = -\frac{\varepsilon\Delta t}{\Delta\Phi}$ $= \frac{0.10\times0.50}{2.0\times10^{-4}}$ $= 250$ turns

PHYSICS IN ACTION ICT

Microphones

A microphone is a type of transducer, transforming energy from one form (an audio signal in the form of soundwaves) to another (electric energy/current). Many microphones operate by taking advantage of Faraday's law of induction. The so-called 'dynamic' microphone uses a tiny coil attached to a diaphragm. When soundwaves hit the diaphragm, the diaphragm moves in response to the sound. If the tiny coil is close to a permanent magnet, the movement of the coil in the magnetic field will induce an emf that varies with the original sound. That induced emf will cause a current to flow in the coil due to Faraday's law of induction.

FIGURE 7.2.2 A diver using a metal detector. If a metal object is found underneath the coil of the detector, an emf will be induced which creates a current that will affect the original current. The direction of the induced current is predicted by using Lenz's law.

Worked example: Try yourself 7.2.2

NUMBER OF TURNS IN A COIL

A coil of cross-sectional area $2.0 \times 10^{-3}\,m^2$ experiences a change in the strength of a magnetic field from 0 to 0.20 T over 1.00 s. If the magnitude of the average induced emf is measured as 0.40 V, how many turns must be on the coil?

LENZ'S LAW AND ITS APPLICATIONS

Lenz's law is a common way of understanding how electromagnetic induction obeys the principles of conservation of energy and explains the direction of the induced emf. It is named after Heinrich Lenz, whose research put a definite direction to the current created by the induced emf resulting from a changing magnetic flux.

Understanding the direction of the current resulting from an induced emf and how it is produced has allowed electromagnetic induction to be used in a vast array of devices that have transformed modern society, in particular in electrical generators. A metal detector is another example of a device that uses Lenz's law (Figure 7.2.2).

The direction of an induced emf

Lenz's law states that an induced emf always gives rise to a current whose magnetic field will oppose the original change in flux.

Figure 7.2.3 applies the law to the relative motion between a magnet and a single coil of wire. Moving the magnet towards or away from the coil will induce an emf in the coil, as there is a change in flux. The induced emf will produce a current in the coil, and this induced current will then produce its own magnetic field. It is worth noting that Lenz's law is a necessary consequence of the law of conservation of energy: if Lenz's law were not true then the new magnetic field created by a changing flux would encourage that change, which would have the effect of adding energy to the universe.

Applying Lenz's law, the magnetic field created by the induced current will oppose the change in flux caused by the movement of the magnet. When the north end of a magnet is brought towards the loop from the right, the magnetic flux from right to left through the loop increases. The induced emf produces a current that flows anticlockwise around the loop when viewed from the right. The magnetic field created by this current, shown by the little circles around the wire, is directed from left to right through the loop. It opposes the magnetic field of the approaching magnet.

If the magnet is moved away from the loop, as in part b of Figure 7.2.3, the magnetic flux from right to left through the loop decreases. The induced emf produces a clockwise current when viewed from the right. This creates a magnetic field that is directed from right to left through the loop. This field is in the same direction as the original magnetic field of the retreating magnet. However, note that it is opposing the change in the magnet's flux through the loop by attempting to replace the declining flux.

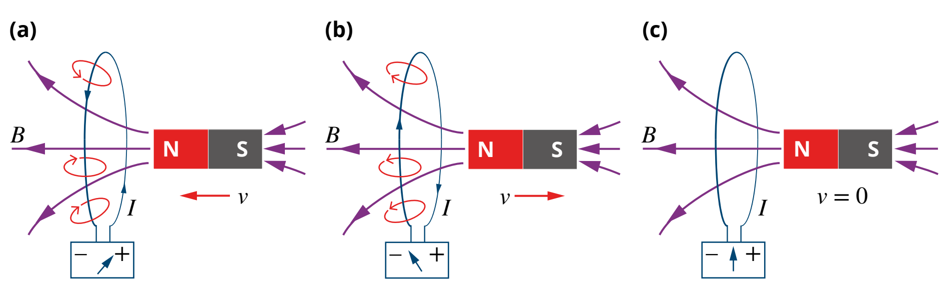


FIGURE 7.2.3 (a) The north end of a magnet is brought towards a coil from right to left, inducing a current that flows anticlockwise. (b) Pulling the north end of the magnet away from the coil from left to right induces a current in a clockwise direction. (c) Holding the magnet still creates no change in flux and hence no induced current.

When the magnet is held stationary, as in part c of Figure 7.2.3, there is no change in flux to oppose and so no current is induced.

The right-hand grip rule and induced current direction

The right-hand grip rule can be used to find the direction of the induced current. Keep in mind that the current must create a magnetic field that opposes the change in flux due to the relative motion of the magnet and conductor. Point your fingers through the loop in the direction of the field that is *opposing* the change and your thumb will then indicate the direction of the conventional current, as shown in Figure 7.2.4.

There are three distinct steps to determine the induced current direction according to Lenz's law:

1. What is the change that is happening?
2. What will *oppose* the change and/or restore the original conditions?
3. What must be the current direction to match this opposition?

These steps will be further examined in Worked example 7.2.3.

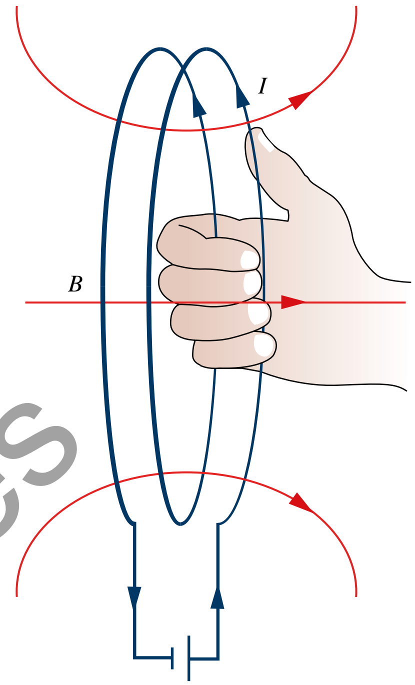
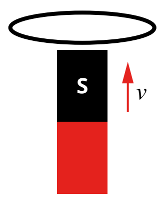


FIGURE 7.2.4 The right-hand grip rule can be used to determine the direction of a magnetic field from a current or vice versa. Your thumb points in the direction of the conventional current in the wire and your curled fingers indicate the direction of the magnetic field through the coil.

Worked example 7.2.3

INDUCED CURRENT IN A COIL FROM A PERMANENT MAGNET

The south pole of a magnet is brought upwards towards a horizontal coil initially held above it. In which direction will the induced current flow in the coil?

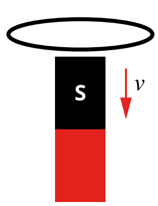


Thinking	Working
Consider the direction of the change in magnetic flux.	The magnetic field direction from the magnet will be downwards towards the south pole. The downward flux from the magnet will increase as the magnet is brought closer to the coil. So the change in flux is increasing downwards.
What will oppose the change in flux?	The induced magnetic field that opposes the change would act upwards.
Determine the direction of the induced current required to oppose the change.	In order to oppose the change, the current direction would be anticlockwise when viewed from above (using the right-hand grip rule).

Worked example: Try yourself 7.2.3

INDUCED CURRENT IN A COIL FROM A PERMANENT MAGNET

The south pole of a magnet is moved downwards away from a horizontal coil held above it. In which direction will the induced current flow in the coil?



Worked example 7.2.4

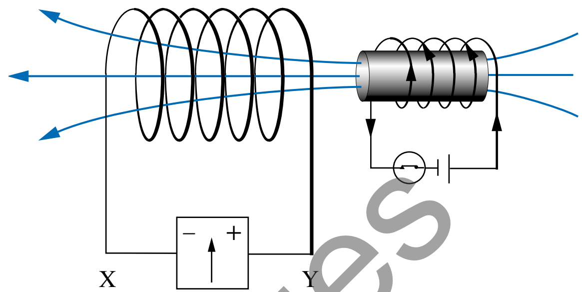
INDUCED CURRENT IN A COIL FROM AN ELECTROMAGNET

Instead of using a permanent magnet to change the flux in the loop as in Worked example 7.2.3, an electromagnet (on the right, in the diagram below) could be used. What is the direction of the current induced in the solenoid when the electromagnet is:

(i) switched on

(ii) left on

(iii) switched off?



Thinking	Working
Consider the direction of the change in magnetic flux for each case.	**(i)** Initially there is no magnetic flux through the solenoid. When the electromagnet is switched on, the electromagnet creates a magnetic field directed to the left. So the change in flux through the solenoid is increasing to the left. **(ii)** While the current in the electromagnet is steady, the magnetic flux through the solenoid is constant and the flux is not changing. **(iii)** In this case, initially there is a magnetic flux through the solenoid from the electromagnet directed to the left. When the electromagnet is switched off, there is no longer a magnetic flux through the solenoid. So the change in flux through the solenoid is decreasing to the left.
What will oppose the change in flux for each case?	**(i)** The magnetic field that opposes the change in flux through the solenoid is directed to the right. **(ii)** There is no change in flux and so there will be no opposition needed and no magnetic field created by the solenoid. **(iii)** The magnetic field that opposes the change in flux through the solenoid is directed to the left.
Determine the direction of the induced current required to oppose the change for each case.	**(i)** In order to oppose the change, the current will flow through the solenoid in the direction from X to Y (or through the meter from Y to X), using the right-hand grip rule. **(ii)** There will be no induced emf or current in the solenoid. **(iii)** In order to oppose the change, the current will flow through the solenoid in the direction from Y to X (or through the meter from X to Y), using the right-hand grip rule.

Worked example: Try yourself 7.2.4

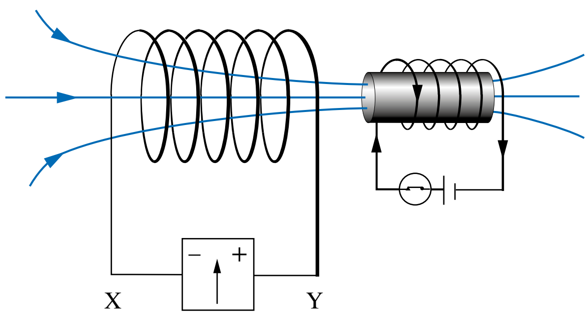
INDUCED CURRENT IN A COIL FROM AN ELECTROMAGNET

What is the direction of the current induced in the solenoid when the electromagnet is:

(i) switched on

(ii) left on

(iii) switched off?



Induced current by changing area

PA 6.3

It's very important to note that an induced emf is created while there is a change in flux, no matter how that change is created. As magnetic flux $\Phi = B_{\|}A$, a change can be created by any method that causes a relative change in the strength of the magnetic field, B, and/or the plane of the area perpendicular to the magnetic field. So an induced emf can be created in three ways:

- by changing the strength of the magnetic field
- by changing the area of the coil within the magnetic field
- by changing the orientation of the coil with respect to the direction of the magnetic field.

Figure 7.2.5 illustrates an example of the direction of an induced current that results during a decrease in the area of a coil.

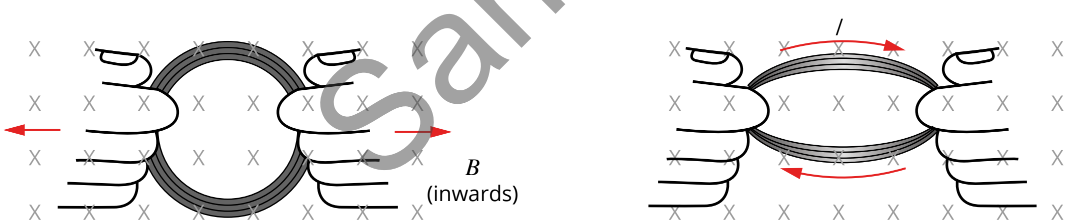


FIGURE 7.2.5 Inducing a current by changing the area of a coil. The amount of flux (the number of field lines) through the coil is reduced and an emf is therefore induced during the time that the change is taking place. The current flows in a direction that creates a field to oppose the reduction in flux into the page.

As the area of the coil decreases due to its changing shape, the flux through the coil (which is directed into the page) also decreases. Applying Lenz's law, the direction of the induced current would oppose this change and will be such that it acts to increase the magnetic flux through the coil into the page. Using the right-hand grip rule, a current would therefore flow in a clockwise direction while the area is changing.

In Figure 7.2.6, the coil is being rotated within the magnetic field. The effect is the same as reducing the area. The amount of flux flowing through the coil is reduced as the coil changes from being perpendicular to the field to being parallel to the field. An induced emf would be created while the coil is being rotated. This becomes particularly important when determining the current direction in a generator.

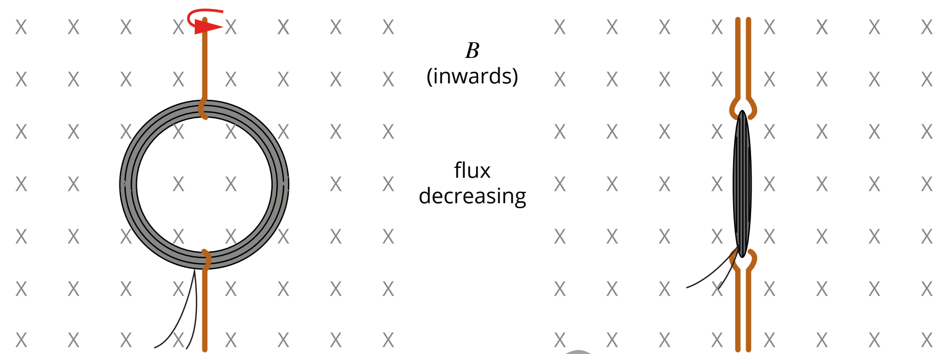
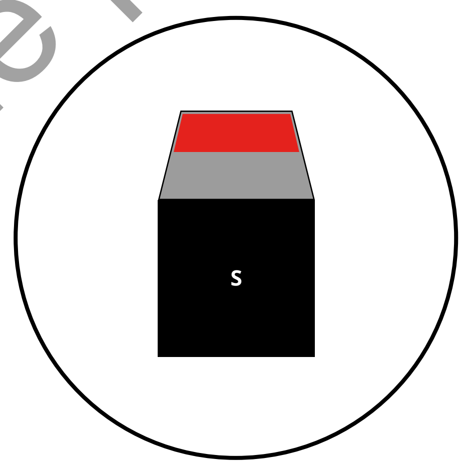


FIGURE 7.2.6 Changing the orientation of a coil within a magnetic field by rotating it reduces the amount of flux through the coil and so induces an emf in the coil while it is being rotated.

Worked example 7.2.5

FURTHER PRACTICE WITH LENZ'S LAW

The north pole of a magnet is moving towards a coil, into the page (the south pole is shown at the top looking down). In what direction will the induced current flow in the coil while the magnet is moving towards the coil?



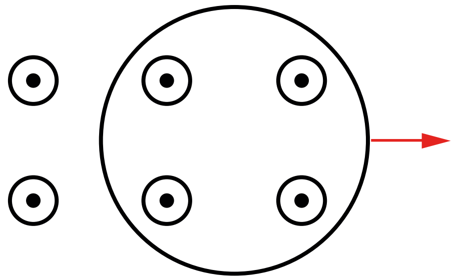
Thinking	Working
Consider the direction of the change in magnetic flux.	The magnetic field direction from the magnet will be away from the north pole, into the page. The flux from the magnet will increase as the magnet is brought closer to the coil. Therefore the change in flux is increasing into the page.
What will oppose the change in flux?	The magnetic field that opposes the change would act out of the page.
Determine the direction of the induced current required to oppose the change.	In order to oppose the change, the current direction would be anticlockwise when viewed from above (using the right-hand grip rule).

Worked example: Try yourself 7.2.5

PA 6.4

FURTHER PRACTICE WITH LENZ'S LAW

A coil is moved to the right and out of a magnetic field that is directed out of the page. In what direction will the induced current flow in the coil while the magnet is moving?



PHYSICSFILE ICT

Eddy currents

Lenz's law is important for many practical applications such as metal detectors, induction stoves and regenerative braking. These all rely on an eddy current, which is a circular electric current induced within a conductor by a changing magnetic field.

Applying Lenz's law, an eddy current will be in a direction that creates a magnetic field that opposes the change in magnetic flux that created it. Thus eddy currents can be used to apply a force that opposes the source of the motion of an external magnetic field. For example, if a metal plate is dragged out of a magnetic field, an eddy current will form within the plate that opposes the change in flux through the area of the plate, and thus opposes the motion of the plate itself due to the interaction of the magnetic fields (Figure 7.2.7).

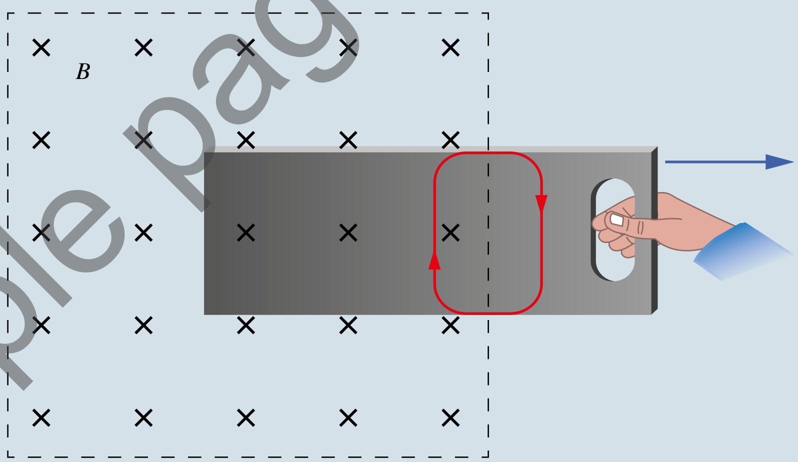


FIGURE 7.2.7 As the metal plate is moved towards the right, out of the magnetic field which is directed into the page, an eddy current forms in a clockwise direction. This eddy current would resist the motion of the plate.

This is the basis of regenerative braking, where the drag of the opposing magnetic field is utilised as a braking force. An eddy current flowing through a conductor with some resistance will also lose energy to the conductor by heating it. This makes eddy currents useful for an induction stovetop, but a potentially major source of energy loss within an AC generator, motor or transformer. Laminated cores with insulating material between the thin layers of iron are used in these applications to reduce the overall conductivity and suppress eddy currents.

The Earth's magnetic field is also a result of eddy currents. The energy that drives the Earth's dynamo comes from the enormous heat produced by radioactive decay deep in the Earth's core. The heat causes huge swirling convection currents of molten iron in the outer core. These convection currents of molten iron act rather like a spinning disk. They are moving in the Earth's magnetic field and so eddy currents are induced in them. It is these eddy currents that produce the Earth's magnetic field.

PHYSICSFILE ICT

Induction stoves

In contrast to a conventional gas or electric stove that heats via radiant heat from a hot source, an induction stove heats via the metal pot in which the food is being cooked. A coil of copper wire is placed within the cooktop (Figure 7.2.8). The AC electricity supply produces a changing magnetic field in the coil. This induces an eddy current in the conductive metal pot. The resistance of the metal in the pot, in which the eddy current flows, transforms electrical energy into heat and cooks the food.

While induction cooktops have only reached the domestic market in relatively recent times, the first patents for induction cookers were issued in the early 1900s. They have significant advantages over traditional electric cooktops in that they allow instant control of cooking power (similar to gas burners), they lose less energy through ambient heat loss and heating time, and they have a lower risk of causing burn injuries. Overall, the heating efficiency of an induction cooktop is around 12% better than traditional electric cooktops and twice that of gas.

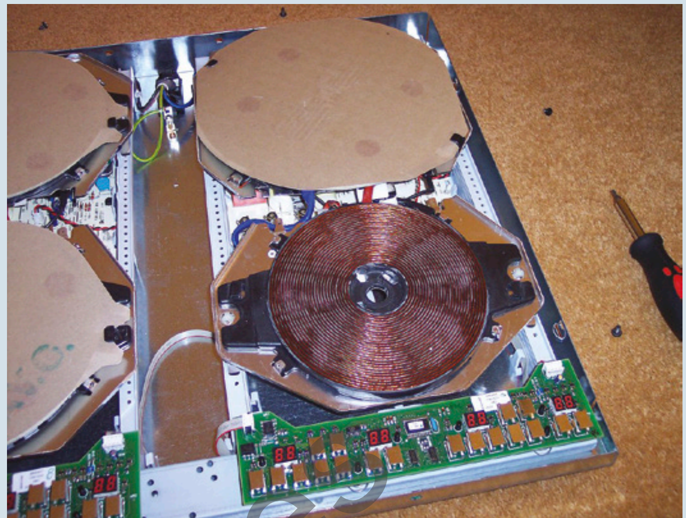


FIGURE 7.2.8 The coil of an induction zone within an induction cooktop. The large copper coil creates an alternating magnetic field.

PHYSICS IN ACTION ICT

The Meissner effect

Superconductivity is a phenomenon that occurs when materials are cooled below a critical temperature (usually close to absolute zero), causing the material to have zero electrical resistance. Superconductors prevent magnetic fields from penetrating their interior, so that if a magnet is brought close to a superconductor it will levitate (Figure 7.2.9). This is known as the Meissner effect, named after the German physicists W. Meissner and R. Ochsenfeld in 1933 who discovered this property of superconductors. The Meissner effect is not the same as induced eddy currents. Eddy currents require a changing magnetic flux, hence the magnet would need to move. Yet in the Meissner effect, the magnet is stationary. Instead, this effect is due to quantum mechanical properties of the superconductor.

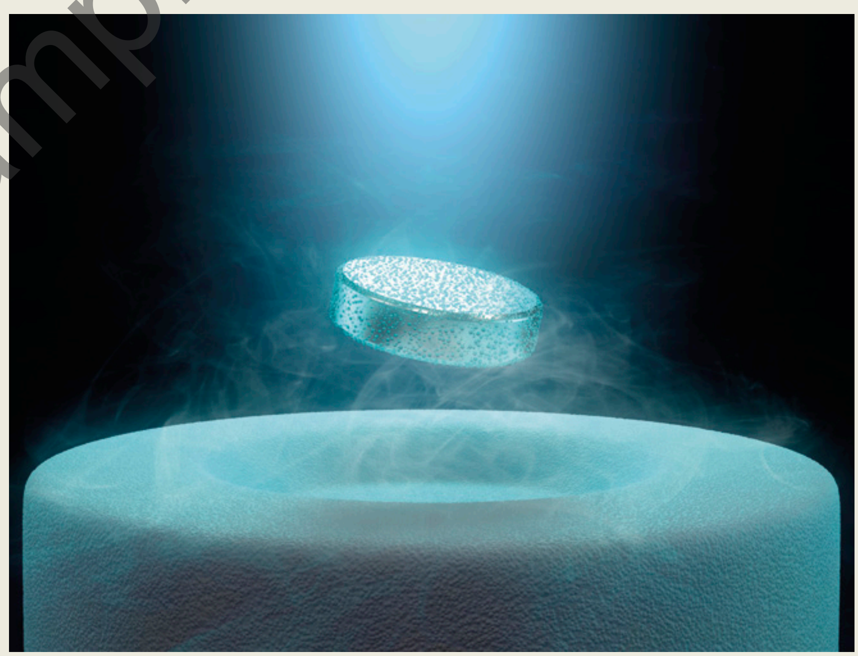


FIGURE 7.2.9 A magnet levitates above a superconductor due to the Meissner effect.

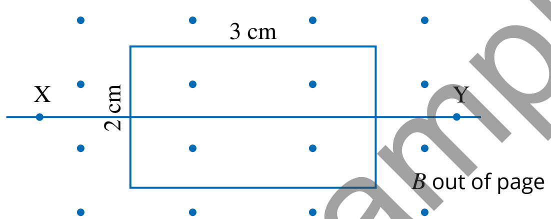
7.2 Review

SUMMARY

- The emf induced in a conducting loop in which there is a changing magnetic flux is proportional to the negative rate of change of flux.
- This is described by Faraday's law of induction: $\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$.
- The negative sign in Faraday's law indicates direction. For questions involving only magnitudes, you can ignore the negative sign in your calculations.
- Lenz's law states that an induced emf always gives rise to a current whose magnetic field will oppose the original change in flux.
- There are three distinct steps to determine the induced current direction according to Lenz's law:
  1 What is the change that is happening?
  2 What will oppose the change and/or restore the original conditions?
  3 What must be the current direction to match this opposition?
- An induced emf can be created in three ways:
  - by changing the strength of the magnetic field
  - by changing the area of the coil within the magnetic field
  - by changing the orientation of the coil with respect to the direction of the magnetic field.

KEY QUESTIONS

The following information relates to questions 1–3.
A single rectangular wire loop is located with its plane perpendicular to a uniform magnetic field of 2.0 mT, directed out of the page, as shown below. The loop is free to rotate about a horizontal axis XY.

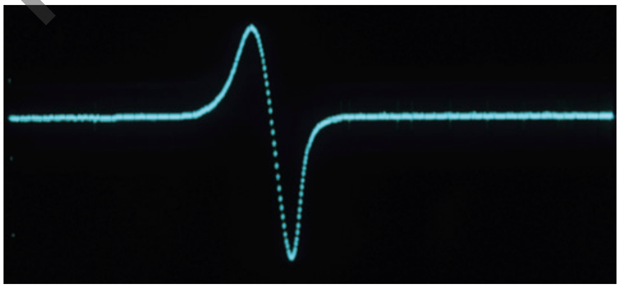


1 How much magnetic flux is threading the loop in this position?

2 The loop is rotated about the axis XY, through an angle of 90°, so that its plane becomes parallel to the magnetic field. How much flux is threading the loop in this new position?

3 If the loop completes one-quarter of a rotation in 40 ms, what is the average induced emf in the loop?

4 When a magnet is dropped through a coil, a voltage sensor will detect an induced voltage in the coil as shown below.



The area under the curve above zero is exactly equal to the area above the curve below zero because:
A The strength of the magnet is the same.
B The area of the coil is the same.
C The strength of the magnet and area of the coil are the same.
D The magnet speeds up as it falls through the coil.

The following information relates to questions 5 and 6.
A coil of 500 turns, each of area 10 cm^2, is wound around a square frame. The plane of the coil is initially parallel to a uniform magnetic field of 80 mT. The coil is then rotated through an angle of 90° so that its plane becomes perpendicular to the field. The rotation is completed in 20 ms.

5 What is the average emf induced in each turn during this time?

6 What is the effect on the average induced emf due to the multiple coils in Question 5?

7.2 Review *continued*

7 A conducting loop is located in an external magnetic field whose direction (but not necessarily magnitude) remains constant. A current is induced in the loop. Which of the following alternatives best describes the direction of the magnetic field due to the induced current?

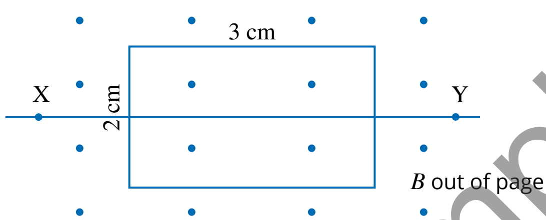
A It will always be in the same direction as the external magnetic field.

B It will always be in the opposite direction to the external magnetic field.

C It will be in the same direction as the external magnetic field if the external magnetic field gets weaker, and it will be in the opposite direction to the external magnetic field if the external magnetic field gets stronger.

D The direction can't be determined from the information supplied.

8 A rectangular conducting loop forms the circuit shown below. The plane of the loop is perpendicular to an external magnetic field whose magnitude and direction can be varied. The initial direction of the field is out of the page.



a When the magnetic field is switched off, what will be the direction of the magnetic field due to the induced current?

A out of the page
B into the page
C clockwise
D anticlockwise
E left to right
F right to left

b When the direction of the external magnetic field is reversed, what is the direction of the magnetic field due to the induced current?

A out of the page
B into the page
C clockwise
D anticlockwise
E left to right
F right to left

7.3 Transformers

When Faraday first discovered electromagnetic induction, he had effectively invented the transformer. A **transformer** is a device for increasing and decreasing an alternating current (AC) voltage. Transformers can be found in many electrical devices: they are an essential part of any electrical distribution system and are the focus of this section (Figure 7.3.1).

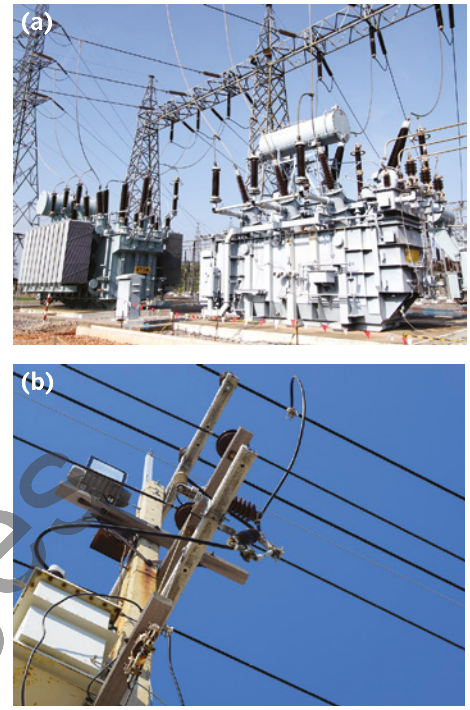


FIGURE 7.3.1 (a) View of transformers at an electrical substation. The substation takes electricity from the distribution grid and converts it to lower voltages used by industrial or residential equipment. (b) More common are the smaller distribution transformers found on every suburban street. See if you can locate at least one on your street.

THE WORKINGS OF A TRANSFORMER

A transformer works on the principle of a changing magnetic flux inducing an emf. No matter what the size or application, a transformer will consist of two coils known as the primary and secondary coils. The changing flux originates with the alternating current supplied to the primary coil. The changing magnetic flux is directed to the secondary coil where the changing flux will induce an emf in that coil (Figure 7.3.2).

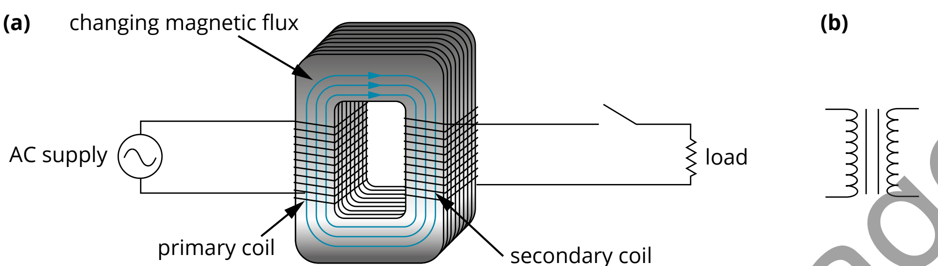


FIGURE 7.3.2 (a) In an ideal transformer, the iron core ensures that all the flux generated in the primary coil also passes through the secondary coil. (b) The symbol used in circuit diagrams for an iron-core transformer.

The two coils can be interwoven using insulated wire or they can be linked by a soft iron core, laminated to minimise eddy current losses. Transformers are designed so that nearly all of the magnetic flux produced by the primary coil will pass through the secondary coil. In an **ideal transformer** the assumption is that this will be 100% efficient and energy losses can be ignored. In a real transformer, this assumption remains a good approximation. Transformers are one of the most efficient devices around, with practical efficiencies often being better than 99%.

AC VERSUS DC

The power distribution system works on alternating current. That may seem odd when many devices run on direct current, but one of the primary reasons is the ease with which alternating current can be transformed from one voltage to another.

A transformer works on the basis of a changing current in the primary coil inducing a changing magnetic flux. This in turn induces a current in the secondary coil. For this to work, the original current must be constantly changing, as it does in an AC supply.

A DC voltage has a constant, unchanging current. With no change in the size of the current, no changing magnetic flux will be created by the primary coil and, hence, no current is induced in the secondary coil. Transformers do not work with the constant current of a DC electrical supply. There will be a very brief induced current when a DC supply is turned on, and a change occurs from zero current to the supply level. There is a similar spike if the DC supply is switched off, but while the DC supply is constant there is no change in magnetic flux to induce a current in the secondary coil.

THE TRANSFORMER EQUATION

When an AC voltage is connected to the primary coil of a transformer, the changing magnetic field will induce an AC voltage of the same frequency as the original supply in the secondary coil. The voltage in the secondary coil will be different and depends upon the number of turns in each coil.

+ ADDITIONAL

Laminations

Eddy currents that are created in the iron core of transformers can generate a considerable amount of heat. Energy that has been lost from the electrical circuit and the transformer as heat may become a fire hazard. To reduce eddy current losses, the transformer core is made of laminations, which are thin plates of iron electrically insulated from each other and placed so that the insulation between the laminations interrupts the eddy currents.

From Faraday's law, the average voltage in the primary coil, V_P, will affect the rate at which the magnetic flux changes:

$$V_P = N_P \frac{\Delta\Phi}{\Delta t}$$

or

$$\frac{\Delta\Phi}{\Delta t} = \frac{V_P}{N_P}$$

where N_p is the number of turns in the primary coil.

The induced voltage in the secondary coil, V_s, will be

$$V_S = N_S \frac{\Delta\Phi}{\Delta t}$$

and

$$\frac{\Delta\Phi}{\Delta t} = \frac{V_S}{N_S}$$

where N_s is the number of turns in the secondary coil.

Assuming that there is little or no loss of flux between the primary and secondary coils, then the flux in each will be the same and

$$\frac{V_P}{N_P} = \frac{V_S}{N_S}$$

or

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

The transformer equation, relating voltage and number of turns in each coil, is:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \text{ or } \frac{V_S}{V_P} = \frac{N_S}{N_P} \text{ or } \frac{V_P}{N_P} = \frac{V_S}{N_S}$$

The magnitude of alternating current (AC) voltage or current is expressed as the peak value, peak-to-peak value or RMS (root mean square) value. As AC current or voltage is a time-varying, sinusoidal value, the peak and peak-to-peak values refer to the height of the sinusoidal waveform (from zero to peak, or negative peak to positive peak). The RMS value is effectively the mean (average) value of the AC supply, and is often the value used in measurements.

The transformer equation explains how the secondary (output) voltage is related to the primary input voltage. Either the rms voltage for both or the peak voltage for both can be used.

A **step-up transformer** increases the secondary voltage compared with the primary voltage. The secondary voltage is greater than the primary voltage and the number of turns in the secondary coil is greater than the number of turns in the primary coil, i.e. if $N_S > N_P$ then $V_S > V_P$.

A **step-down transformer** decreases the secondary voltage compared with the primary voltage. The secondary voltage is less than the primary voltage and the number of turns in the secondary coil is less than the number of turns in the primary coil, i.e. if $N_S < N_P$ then $V_S < V_P$.

Worked example 7.3.1

TRANSFORMER EQUATION—VOLTAGE

A transformer is built into a portable radio to reduce the 240 V supply voltage to the required 12 V for the radio. If the number of turns in the secondary coil is 100, what is the number of turns required in the primary coil?

Thinking	Working
State the relevant quantities given in the question. Choose a form of the transformer equation with the unknown quantity in the top left position.	$V_S = 12\text{ V}$ $V_P = 240\text{ V}$ $N_S = 100$ turns $N_P = ?$ $\frac{N_P}{N_S} = \frac{V_P}{V_S}$
Substitute the quantities into the equation, rearrange and solve for N_P.	$\frac{N_P}{100} = \frac{240}{12}$ $N_P = \frac{100 \times 240}{12}$ $= 2000$ turns

Worked example: Try yourself 7.3.1

TRANSFORMER EQUATION—VOLTAGE

A transformer is built into a phone charger to reduce the 240 V supply voltage to the required 6 V for the charger. If the number of turns in the secondary coil is 100, what is the number of turns required in the primary coil?

POWER OUTPUT

Although a transformer very effectively increases or decreases an AC voltage, energy conservation means that the output power cannot be any greater than the input power. Since a well-designed transformer with a laminated core can be more than 99% efficient, the power input can be considered equal to the power output, making it an 'ideal' transformer.

Since power supplied is $P = VI$, then:

$$V_P I_P = V_S I_S$$

The transformer equation can then be written in terms of current, I.

The transformer equation, relating current and the number of turns in each coil:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P} \text{ or } \frac{I_S}{I_P} = \frac{N_P}{N_S} \text{ or } \frac{I_P}{N_S} = \frac{I_S}{N_P}$$

Note carefully that the number-of-turns ratio for currents is the inverse of that for the transformer equation written in terms of voltage.

A transformer will be overloaded if too much current is drawn and the resistive power loss in the wires becomes too great. There will be a point at which the transformer starts to overheat rapidly. For this reason, it is important not to exceed the rated capacity of a transformer.

Worked example 7.3.2

TRANSFORMER EQUATION—CURRENT

A radio with 2000 turns in the primary coil and 100 turns in its secondary coil draws a current of 4.0 A. What is the current in the primary coil?

Thinking	Working
State the relevant quantities given in the question. Choose a form of the transformer equation with the unknown quantity in the top left position.	$I_S = 4.0$ A $N_S = 100$ turns $N_P = 2000$ turns $I_P = ?$ $\frac{I_P}{I_S} = \frac{N_S}{N_P}$
Substitute the quantities into the equation, rearrange and solve for I_P.	$\frac{I_P}{4.0} = \frac{100}{2000}$ $I_P = \frac{4.0 \times 100}{2000}$ $= 0.20$ A

Worked example: Try yourself 7.3.2

TRANSFORMER EQUATION—CURRENT

A phone charger with 4000 turns in the primary coil and 100 turns in its secondary coil draws a current of 0.50 A. What is the current in the primary coil?

PHYSICSFILE ICT S

Standby power

Because very little current will flow in the primary coil of a good transformer to which there is no load connected, the transformer will use little power when not in use. However, this 'standby power' can add up to around 10% of power use. This is why devices such as TVs and computers should be switched completely off when not in use. Over the whole community, standby power amounts to megawatts of wasted power and unnecessary greenhouse emissions! Special switches, such as the 'Ecoswitch' shown below, have been developed that can be connected between the power outlet and the device to make it easier to remember to turn devices completely off when not in use.

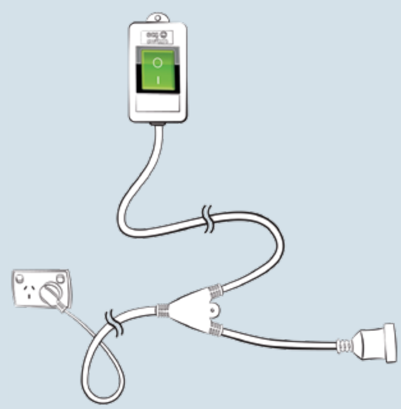


FIGURE 7.3.3 Standby switches such as the 'Ecoswitch' make it easier and more convenient to turn devices completely off when not in use, saving up to 10% on power bills.

Worked example 7.3.3

TRANSFORMERS—POWER

The power drawn from the secondary coil of the transformer by a portable radio is 48 W. What power is drawn from the mains supply if the transformer is an ideal transformer?

Thinking	Working
The energy efficiency of a transformer can be assumed to be 100%. The power in the secondary coil will be the same as that in the primary coil.	The power drawn from the mains supply is the power in the primary coil, which will be the same as the power in the secondary coil: $P = 48\,\text{W}$.

Worked example: Try yourself 7.3.3

TRANSFORMERS—POWER

The power drawn from the secondary coil of the transformer by a phone charger is 3 W. What power is drawn from the mains supply if the transformer is an ideal transformer?

POWER FOR CITIES: LARGE-SCALE AC SUPPLY

In your school experiments using electrical circuits, it is likely that you have ignored the resistance of the connecting wires because the wires (generally made from copper) are good conductors, and so the resistance is very small over short distances. However, over large distances, even relatively good electrical conductors like copper have a significant resistance.

Modern cities use huge amounts of electrical energy, most of which is supplied from power stations built at a considerable distance from the metropolitan areas. The efficient transmission of the electrical energy with the least amount of power loss over that distance is therefore a very important consideration for electrical engineers, particularly given the vast distances between population centres in Australia.

The power lost in an electrical circuit is given by $\Delta P = \Delta VI$, where ΔV is the voltage drop across the load. Recalling Ohm's law, $\Delta V = IR$, and substituting it into the power equation, the power loss can be expressed in terms of either current and load resistance or voltage drop and load resistance:

$$P_{\text{loss}} = \Delta VI = I^2R = \frac{\Delta V^2}{R}$$

By considering the form of the equation including the current carried by the circuit and its electrical resistance ($P_{\text{loss}} = I^2R$), it is clear that transmitting large amounts of power using a large current will create very large power losses. If the current in the power lines can be reduced, it will significantly reduce the power loss. Since the power loss is proportional to the square of the current, then if the current is reduced by a factor of 3, for example, the power loss will be reduced by a factor of 3^2 or 9.

The challenge, then, is to transmit the large amounts of power being produced at power stations using a very low current. Transformers are the most common solution to this problem. Using a step-up transformer near the power station, the voltage is increased by a certain factor and, importantly, the current is decreased by the same factor. Due to the $P_{\text{loss}} = I^2R$ equation, the power lost during transmission is reduced by the square of that factor.

At this point you might be confused by the alternative equation for power loss: $P_{\text{loss}} = \frac{\Delta V^2}{R}$. A simple misunderstanding could make you think that increasing the voltage through the use of a step-up transformer would actually lead to greater power loss, if you use this equation to calculate power loss. However, ΔV represents the voltage drop in a circuit. You must be careful not to confuse the voltage being transmitted along the wires with the voltage drop across the wires. So, even though the voltage being transmitted is increased through the use of a step-up transformer, the voltage drop across the wires would be reduced since $\Delta V = IR$, and thus the power loss would also be reduced.

AC power from the generator is readily stepped up by a transformer to between 240 kV and 500 kV prior to transmission. Once the electrical lines reach the city, the voltage is stepped down in stages at electrical substations for distribution. The power lines in streets will have a voltage of around 2400 V, before being stepped down via small distribution transformers to 240 V for home use.

Worked example 7.3.4

TRANSMISSION-LINE POWER LOSS

300 MW is to be transmitted from the Murray 1 power station in the Snowy Mountains Scheme to Sydney, along a transmission line with a total resistance of 1.0 Ω. What would be the total transmission power loss if the initial voltage along the line was 250 kV?

Thinking	Working
Convert the values to SI units.	$P = 300\,\text{MW} = 300 \times 10^6\,\text{W}$ $V = 250\,\text{kV} = 250 \times 10^3\,\text{V}$
Determine the current in the line based on the required voltage.	$P = VI \therefore I = \frac{P}{V}$ $I = \frac{300 \times 10^6}{250 \times 10^3}$ $= 1200\,\text{A}$
Determine the corresponding power loss.	$P_{loss} = I^2R$ $= 1200^2 \times 1$ $= 1.4 \times 10^6\,\text{W}$ or $1.4\,\text{MW}$

Worked example: Try yourself 7.3.4

TRANSMISSION-LINE POWER LOSS

300 MW is to be transmitted from the Murray 1 power station in the Snowy Mountains Scheme to Sydney, along a transmission line with a total resistance of 1.0 Ω. What would be the total transmission power loss if the voltage along the line was 500 kV?

Worked example 7.3.5

VOLTAGE DROP ALONG A TRANSMISSION LINE

Power is to be transmitted along a transmission line with a total resistance of 1.0 Ω. The current is 1200 A. What voltage would be needed at the power generation end of the transmission line to achieve a supply voltage of 250 kV? Give your answer to four significant figures.

Thinking	Working
Determine the voltage drop along the transmission line.	$\Delta V = IR$ $= 1200 \times 1.0$ $= 1200\,\text{V}$
Determine the initial supply voltage.	$V_{initial} = V_{supplied} + \Delta V$ $= 250 \times 10^3 + 1200$ $= 251200\,\text{V}$ or $251.2\,\text{kV}$

Worked example: Try yourself 7.3.5

VOLTAGE DROP ALONG A TRANSMISSION LINE

Power is to be transmitted along a transmission line with a total resistance of 1.0 Ω. The current is 600 A. What voltage would be needed at the power generation end of the transmission line to achieve a supply voltage of 500 kV? Give your answer to four significant figures.

WS 6.5

PA 6.5

PHYSICS IN ACTION ICT

The War of Currents

AC and DC power supplies have been in competition for nearly as long as humans have been generating electricity. The heated debates about the benefits and disadvantages of each type of current prompted what has been called the 'War of Currents' in the late 1800s. During this time Thomas Edison, an American inventor and businessman, had created the Edison Electric Light Company that he hoped would supply electricity to large parts of America with his DC generators. Meanwhile, Nikola Tesla, a Serbian-American physicist, had invented the AC induction motor and, with financial support from George Westinghouse, hoped AC would become the dominant power supply. Ultimately, the ease with which AC could be stepped up using transformers for long-distance transmission with minimal power loss (as discussed in detail throughout this chapter) proved to be the prevailing benefit that led to AC winning the 'war'. However, in his attempt to win the competition, Edison attempted to portray the high-voltage AC power as terrifyingly dangerous by using it to electrocute elephants and by inventing the AC-powered electric chair for the American government to execute prisoners on death row.

While AC power is now universal in large-scale power distributions, there is a limit to how high the voltage of an AC system can go and still be efficient. Above approximately 100 kV, corona loss (due to the high-voltage ionising air molecules) begins to occur, and above 500 kV it no longer becomes feasible to transmit electric power due to these effects.

LARGE-SCALE ELECTRICAL DISTRIBUTION SYSTEMS

Large-scale energy transmission is done through an interconnected grid between the power stations and the population centres where the bulk of the electrical energy is used. A wide-area synchronous grid, also known as an interconnection, directly connects a number of generators, delivering AC power with the same relative phase, to a large number of consumers.

No matter the source, the path the electrical power takes to the final consumer is very similar (Figure 7.3.4). Step-up transformers in a large substation near the power station will raise the voltage from that initially generated to 240 000 V (240 kV) or more. The electrical power will then be carried via high-voltage transmission lines to a number of substations near key centres of demand. Substations with step-down transformers then reduce the voltage to more safe levels for distribution underground or via the standard 'electricity pole' you would be familiar with around city and country areas. Each group of 10–15 houses will be supplied by a smaller distribution transformer, mounted on the poles, which reduces the voltage down to the 240 V AC rms voltage that home and business installations are designed to run on (see Figure 7.3.4).

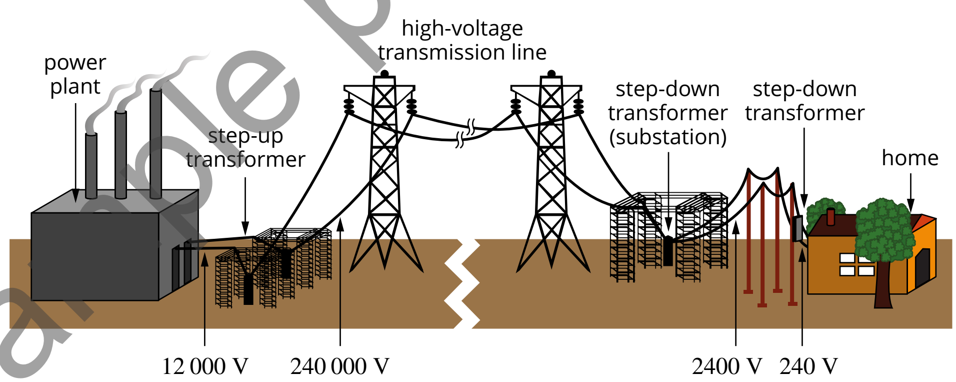


FIGURE 7.3.4 Transmitting electric power from a generator to the home uses AC power, so transformers can be used to minimise power losses through the system.

The use of AC as the standard for distribution allows highly efficient and relatively cheap transformers to convert the initial voltages created at the power station to much higher levels. The same power transmitted at a higher voltage requires less current and therefore less power loss. If it were not for this, the resistance of the transmission wires would need to be significantly reduced, which would require more copper in order to increase their cross-sectional area. This is both expensive and heavy. Less metal makes cables lighter and thinner, and the supporting towers themselves can be comparatively shorter, cheaper and lighter to build.

7.3 Review

SUMMARY

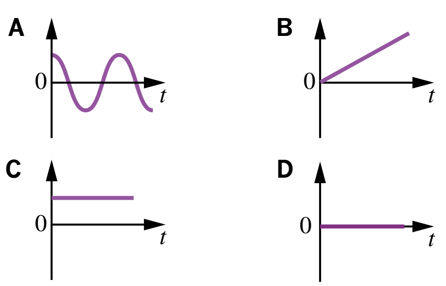
- A transformer works on the principle of a changing magnetic flux inducing an emf. No matter what the size or application, it will consist of two coils known as the primary and secondary coils.
- Ideal transformers are 100% efficient; real transformers are often over 99% efficient, and for this reason power losses within the transformer can be ignored in calculations.
- The transformer equation can be written in different versions but is based on:
$\frac{V_P}{V_S} = \frac{N_P}{N_S}$
- A *step-up* transformer *increases* the secondary voltage compared with the primary voltage.
- A *step-down* transformer *decreases* the secondary voltage compared with the primary voltage.
- The transformer equation can also be written in terms of current, i.e.:
$\frac{I_P}{I_S} = \frac{N_S}{N_P}$ or $V_P I_P = V_S I_S$
- Transformers will not work with DC voltage since it has a constant, unchanging current that creates no change in magnetic flux.
- The power supplied in an electrical circuit is given by:
$P = VI$
- The power lost in an electrical circuit is given by:
$P = I^2R$
- The AC electrical supply from a generator is readily stepped up or down by transformers, hence AC is the preferred form of electrical energy in large-scale transmission systems.

KEY QUESTIONS

1 A non-ideal transformer has a slightly smaller power output from the secondary coil than input to the primary coil. The voltage and current in the primary coil are denoted V_1 and I_1 respectively. The voltage and current in the secondary coil are denoted V_2 and I_2 respectively. Which of the following expressions describes the power output in the secondary coil?

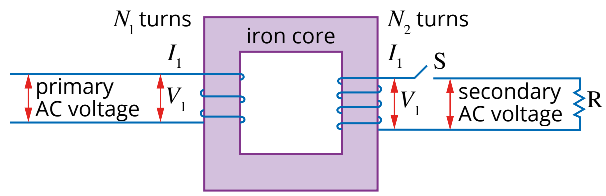
A $V_1 I_1$
B $V_2 I_2$
C $V_1 I_2$
D $I_2{}^2 R$

2 A voltage sensor is connected to the output of a transformer and a series of different inputs is used. Which of the following graphs is the most likely output displayed on a voltage graph for a steady DC voltage input?



3 A security light is operated from a mains voltage 240 V rms through a step-down transformer with 800 turns on the primary winding. The security light operates normally on an rms voltage of 12 V.
How many turns are on the secondary coil?

4 The figure below depicts an iron-core transformer. An alternating voltage applied to the primary coil produces a changing magnetic flux. The secondary circuit contains a switch, S, in series with a resistor, R. The number of turns in the primary coil is N_1 and in the secondary coil, N_2. The power in the first coil is P_1 and in the second coil, P_2. Assume that this is an ideal transformer.



a Write an equation that defines the relationship between the power in the primary coil, P_1, and the power in the secondary coil, P_2.

b Write an equation that defines the relationship between the current in the secondary coil, I_2, and the current in the primary coil, I_1, in terms of the number of turns in each coil.

5 A solar-powered generator produces 5.0 kW of electrical power at 500 V. This power is transmitted to a distant house via twin cables of total resistance 4.0 Ω. What is the total power loss in the cables?

7.3 Review *continued*

6 A 100 km transmission line made from aluminium cable has a total resistance of 10 Ω. The line carries the electrical power from a 500 MW power station to a substation. If the line is operating at 250 kV, what is the power loss in the line?

7 A power station generates 500 MW of power to be used by a town 100 km away. The power lines between the power station and the town have a total resistance of 2.0 Ω.

   a If the power is transmitted at 100 kV, what current would be required?

   b What voltage would be available at the town? Give your answer in kilovolts (kV).

8 Power loss can be expressed by the formula $P = \frac{\Delta V^2}{R} = I^2R$. Therefore, select which of the following statements is true, and justify why the other response is incorrect:

   A The greater the voltage being transmitted in a transmission line, the greater the power loss.

   B The greater the current in the transmission line, the greater the power loss.

Chapter review

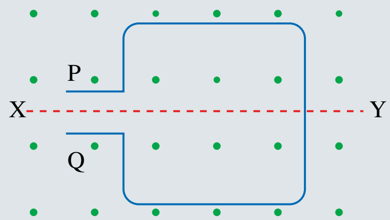
07

KEY TERMS

electromagnetic induction
emf
Faraday's law
ideal transformer
induced current
Lenz's law
magnetic flux
magnetic flux density
step-down transformer
step-up transformer
transformer

REVIEW QUESTIONS

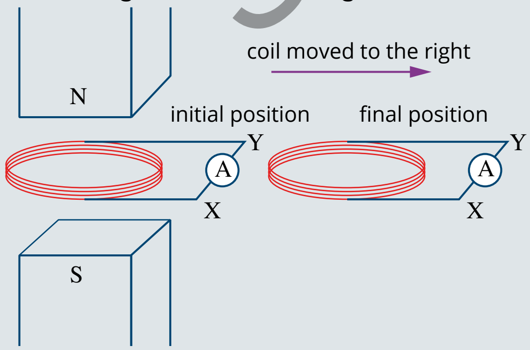
1 A rectangular coil of area 40 cm^2 and resistance 1.0 Ω is located in a uniform magnetic field $B = 8.0 \times 10^{-4}$ T which is directed out of the page. The plane of the coil is initially perpendicular to the field as depicted in the diagram below.



a What is the magnitude of the emf induced in the coil when the strength of the magnetic field is doubled in a time of 1.0 ms?

b What is the direction of the current caused by the induced emf in the coil when the strength of the magnetic field is doubled in a time of 1.0 ms?

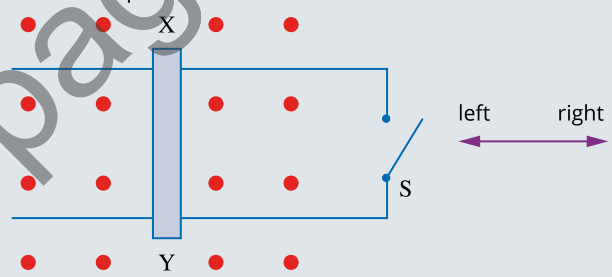
2 During a physics experiment a student pulls a horizontal circular coil from between the poles of two magnets in 0.10 s. The initial position of the coil is entirely in the field, while the final position is free of the field. The coil has 40 turns, each of radius 4.0 cm. The field strength between the magnets is 20 mT.



a What is the magnitude of the average emf induced in the coil as it is moved from its initial position to its final position?

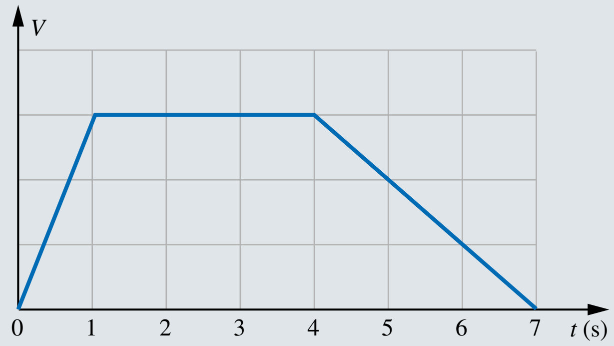
b What is the direction of the current in the coil caused by the induced emf?

3 A copper rod, XY, of length 20 cm is free to move along a set of parallel conducting rails as shown in the following diagram. These rails are connected to a switch, S, which completes a circuit when it is closed. A uniform magnetic field of strength 10 mT, directed out of the page, is established perpendicular to the circuit. S is closed and the rod is moved to the right with a constant speed of 2.0 m s^{-1}.

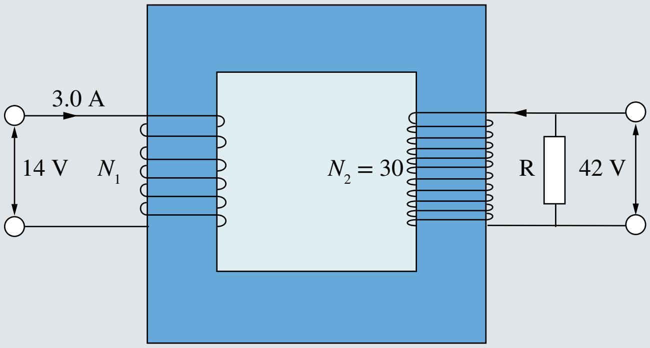


What is the direction of the current through the rod caused by the induced emf?

4 Coils S_1 and S_2 are close together and linked by a soft iron core. The emf in S_1 varies as shown in the graph below. Draw a line graph to show the shape of the variation of the current in S_2.



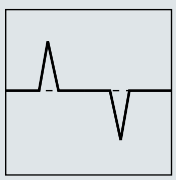
The following information relates to questions 5 and 6.
An ideal transformer is operating with an input voltage of 14 V and primary current of 3.0 A. The output voltage is 42 V. There are 30 turns in the secondary winding.



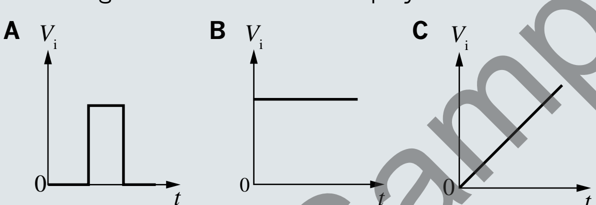
5 What is the output current?

6 How many turns are there in the primary coil?

7 The following diagram shows a graph of induced voltage versus time as it appears on the screen of a cathode ray oscilloscope.



Which of the following input voltages would produce the voltage shown in the CRO display?



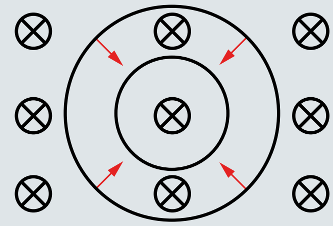
The following information refers to questions 8 and 9.
A student builds a simple alternator consisting of a coil containing 500 turns, each of area 10 cm^2, mounted on an axis that can rotate between the poles of a permanent magnet of strength 80 mT. The alternator is rotated at a frequency of 50 Hz.

8 Find the average emf of the alternator.

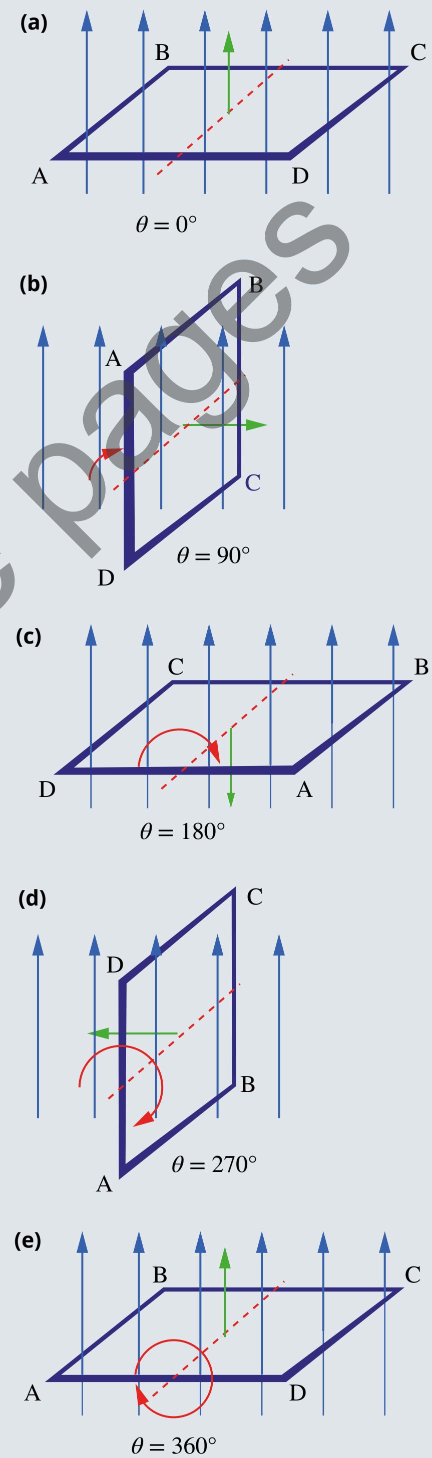
9 Explain what the effect will be on the average emf when the frequency is doubled to 100 Hz.

10 A generator is to be installed in a farm shed to provide 240 V power for the farmhouse. A twin-conductor power line with a total resistance of 8 Ω already exists between the shed and house. The farmer has seen a cheap 240 V DC generator advertised and is tempted to buy it.
Identify and explain two significant problems that you foresee with using the 240 V DC generator.

11 A coil in a magnetic field directed into the page is reduced in size. In what direction will the induced current flow in the coil while the coil is being reduced in size?



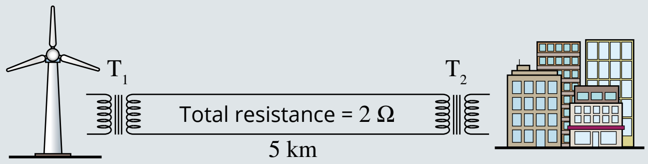
12 A single loop of wire is rotated within a magnetic field, *B*, as shown below.



While the coil is rotating, an emf will be generated as a result of which sides of the coil? Give a reason for your answer.

The following information relates to questions 13–16.

A wind turbine runs a 150 kW generator with an output voltage of 1000 V. The voltage is increased by a transformer T_1 to 10 000 V for transmission to a town 5 km away through power lines with a total resistance of 2 Ω. Another transformer, T_2, at the town reduces the voltage to 250 V. Assume that there is no power loss in the transformers (i.e. they are 'ideal').



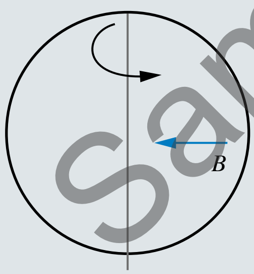
13 What is the current in the power lines?

14 What is the voltage at the input to the town transformer T_2?

15 What is the transmission power loss through the wires?

16 It is suggested that some money could be saved from the scheme by removing the first transformer. Explain, using appropriate calculations, whether this is a good plan.

17 A coil is rotated about its vertical axis such that the left-hand side would be coming out of the page and the right-hand side would be going into it. A magnetic field runs from right to left across the page. In what direction would the induced current in the coil flow?



18 A student has a flexible wire coil of variable area of 100 turns and a strong bar magnet, which has been measured to produce a magnetic field of strength B = 100 mT a short distance from it. She has been instructed to demonstrate electromagnetic induction by using this equipment to light up an LED rated at 1.0 V. Explain, including appropriate calculations, one method with which she could complete this task.

19 A wire coil consisting of a single turn is placed perpendicular to a magnetic field that experiences a decrease in strength of 0.10 T in 0.050 s. If the emf induced in the coil is 0.020 V, what is the area of the coil?

20 A wire coil consisting of 100 turns with an area of 50 cm^2 is placed inside a vertical magnetic field of strength 0.40 T, and then rotated about a horizontal axis. For each quarter turn, the average emf induced in the coil is 1600 mV. Calculate the time taken for a quarter turn of the coil.

21 After completing the activity on page 189, reflect on the inquiry question: How are electric and magnetic fields related?