CHAPTER 6

# Electromagnetic induction

*The relative motion between a conductor and magnetic field is used to generate an electrical voltage*

### Introduction

British scientist Michael Faraday was the first person to realise that a changing magnetic field was able to produce electricity, a phenomenon known as electromagnetic induction. In 1831, after a series of experiments, Faraday stated his law of electromagnetic induction, which quantitatively described the process. The understanding of electromagnetic induction was further improved by Lenz's law, proposed by the Russian physicist Heinrich Friedrich Emil Lenz (1804–65) in 1834.

Electromagnetic induction provides a means of converting mechanical energy into electrical energy; this later becomes the principle for electric generators. Electromagnetic induction also has other useful applications and these will be described in this chapter.

**Definition**

**Electromagnetic induction** is the interaction between magnetic fields and conductors to generate electricity.

## 6.1 Michael Faraday's discovery of electromagnetic induction

### ■ *Outline Michael Faraday's discovery of the generation of an electric current by a moving magnet*

Hans Christian Oersted, a Danish physicist and chemist, was the first person to observe the deflection of a compass needle when placed near a current-carrying wire. He deduced that a current-carrying wire must produce a magnetic field around it. This discovery established the link between electricity and magnetic fields, and initiated the study of electromagnetism.

Not surprisingly, thoughtful scientists wondered: if electricity could produce magnetic fields, why couldn't a magnetic field produce electricity? Many scientists started to investigate ways of using magnetic fields to produce electricity, but unfortunately none of them succeeded. The problem lay in their failure to realise the necessity of a **changing magnetic field** in the generation of electricity. The British chemist and physicist Michael Faraday was the first scientist to solve this riddle. (Although it was believed that Joseph Henry established the theory earlier.) He successfully demonstrated the generation of electricity using a changing magnetic field, and proposed the theory of electromagnetic induction.

So for now, remember: *In order to produce electricity, a changing magnetic field is essential.*

## ■ *Outline Michael Faraday's discovery of the generation of an electric current by a moving magnet*

PFA H1

'Evaluates how major advances in scientific understanding and technology have changed the direction or nature of scientific thinking'

### Why was this discovery a major advance in scientific understanding?

In 1819, Oersted had shown that an electric current produces a magnetic field. Faraday mapped the shape of this field in 1821, and in 1831 was finally able to induce a current in a conductor when the conductor was subjected to a *changing* magnetic field.

Being able to induce a current using a change in a magnetic field was the missing link in the evidence that tied electricity and magnetism together, a phenomenon now known broadly as *electromagnetism.*

### How did it change the direction or nature of scientific thinking?

In the years following his discovery of electromagnetic induction, Faraday changed his thinking on the nature of electricity. Rather than being a fluid, Faraday envisaged (wrongly) that electricity is a force that could be passed between particles of matter. In 1864, James Clerk Maxwell published his equations showing light to be a form of electromagnetism—and that it was the changing electric and magnetic fields that caused the propagation of light.

### Evaluation of Faraday's discovery of electromagnetic induction

Faraday's discovery was extremely valuable. It led to further work and discoveries in the field of electromagnetism. It also caused a change in the understanding of the nature and behaviour of electricity and magnetism in general, enabling the development of electric generators, which subsequently led to the widespread use of electricity for lighting through the 1880s and beyond.

#### USEFUL WEBSITES

WWW

**Details and Java animation of Faraday's experiment:**
**http://micro.magnet.fsu.edu/electromag/java/faraday/**

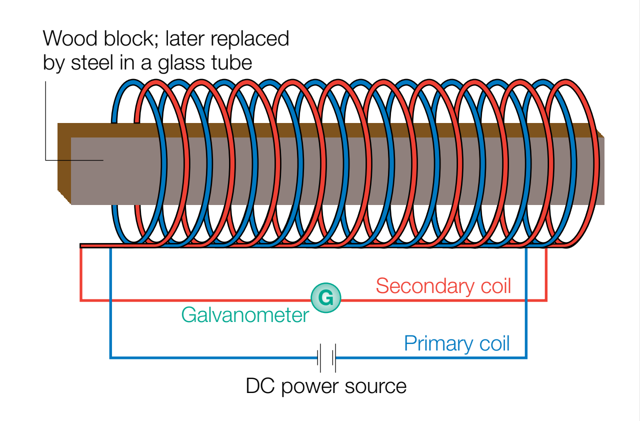
**The Royal Institution of Great Britain's resource on Faraday (and others):**
**http://www.rigb.org/rimain/heritage/faradaypage.jsp**

### Faraday's experiment on electromagnetic induction

In Faraday's early experiments, he wound a copper wire around a piece of wood, and connected the ends to a DC power source; this coil of wire was termed the primary coil. He then wound another copper wire in between the primary coil, as shown in Figure 6.1. The ends of the second wire were connected to a galvanometer, and this coil is referred to as the secondary coil.

When he switched on the power source attached to the primary coil, the meter registered a very small and momentary reading of electricity, then dropped to zero. It remained zero for the rest of the period while the current was on. When the current was switched off, the meter again registered a reading

**Figure 6.1** Faraday's early experiments on electromagnetic induction



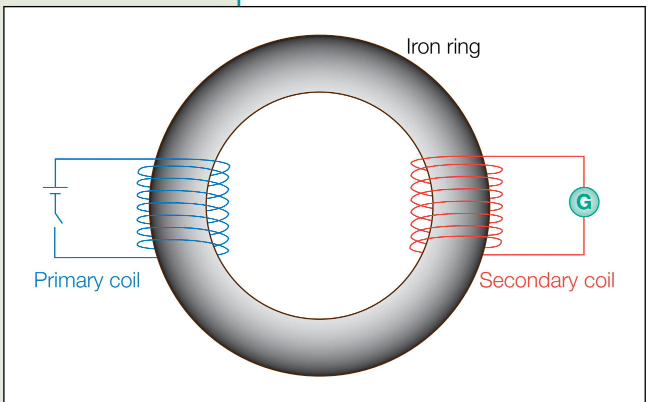



**Figure 6.2**
Mutual induction experiment

then dropped to and remained at zero; however, this time, the needle of the meter swung in the opposite direction to the initial movement.

The wooden block was later replaced by a glass tube with a steel needle inserted inside. A similar procedure was carried out and similar results were observed, except that the current registered was slightly bigger.

Later, in order to reinforce the concept of electromagnetic induction, Faraday conducted a different experiment using an iron ring. A primary copper coil was wound on one side of the ring and a secondary coil was wound on the other side as shown in Figure 6.2.

When the DC power source was switched on and then off as in the previous experiment, a similar pattern of readings was observed in the galvanometer. However, this time, the current registered was much greater.

**Definition**

This phenomenon, where the current in one circuit will induce a current in another circuit nearby, is called **mutual induction**.

## The importance of a changing magnetic field to electromagnetic induction

Why was there a momentary flow of current in the secondary coil only when the DC power was switched on or off in the primary coil, but no current registered while the power source was left on?

When the DC power source is switched on, the current does not reach its maximum value in the primary circuit instantaneously; instead, the current builds up to this value over a very short time. Hence there is a brief period of increasing current, and since the strength of the magnetic field is proportional to the current, this is also a momentary period of increasing magnetic field strength. This increasing, therefore *changing*, magnetic field induces an EMF or current in the secondary coil.

**NOTE:** EMF stands for **electromotive force**. For the purposes of this chapter, it has the same meaning and unit as voltage. An EMF in a closed circuit will cause a current to flow.

However, the current quickly reaches its maximum value in the primary circuit and will remain at this value as long as there is a supply of DC power. This is a period of constant current hence constant magnetic field, and consequently no electricity will be induced. Therefore, after a brief moment, the reading on the meter drops to zero.

When the DC power source is switched off, there is no longer a supply of voltage to the primary coil. However, the current takes a brief moment to drop back to zero. This decrease in current also produces a decrease in the strength of the magnetic field. Again, this *changing* magnetic field causes another momentary flow of electricity in the secondary coil, but in the opposite direction.

## Faraday's electromagnetic induction experiment with moving magnets

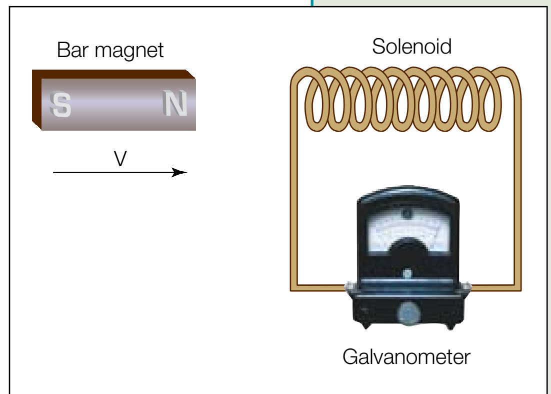



**Figure 6.3 (a)** When the magnet is pushed into the coil

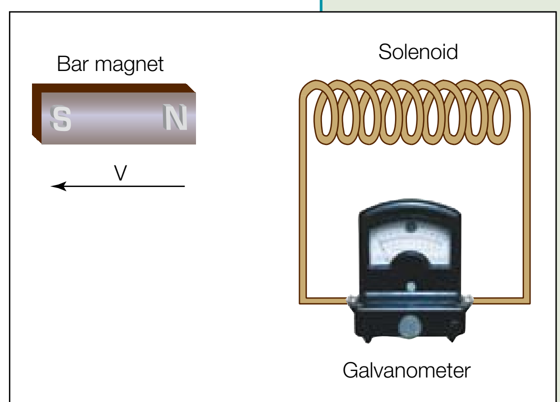



**Figure 6.3 (b)** When the magnet is withdrawn from the coil

There are many ways we can create a changing magnetic field. One common way is to have relative motion between the coil or the conduct and the magnetic field or the object that is creating the magnetic field.

In one of Faraday's later experiments, he demonstrated the effect of moving magnets on inducing electricity in a coil. He wound a coil with many turns and connected the coil to a galvanometer. He then pushed a magnet towards the coil and observed a reading on the meter (see Fig. 6.3a). However, when he stopped moving the magnet, the reading of the meter dropped to zero. As he withdrew the magnet, the meter again registered a reading; however, this time, the needle swung to the other side, showing the induced electricity was flowing in the opposite direction (see Fig. 6.3b).

When the magnet was pushed in and withdrawn more quickly, a similar pattern was observed on the meter, except the size of the induced EMF or current was much bigger.

The theory behind the experiment is as follows: as the magnet is pushed closer to the coil, the magnetic field strength experienced by the coil increases, hence this **changing** of the magnetic field will induce an EMF in the coil. However, when the magnet is not moving, there is no change in the magnetic field and no EMF is induced. Finally, when the magnet is withdrawn from the coil, there is again a *changing* magnetic field, thus an EMF will be induced. However, since now the magnetic field is decreasing in strength, the EMF induced is in the opposite direction.

When the magnet is moved in and out more quickly, there is simply a **greater rate of change** of magnetic field, therefore, the induced EMF or current is bigger (see Faraday's law).

The direction in which the induced electricity will flow will be covered in detail in the section Lenz's law.

# 6.2 Magnetic field lines, magnetic flux and magnetic flux density

- ***Define magnetic field strength* B *as magnetic flux density***
- ***Describe the concept of magnetic flux in terms of magnetic flux density and surface area***

## Magnetic field lines

As we saw in Chapter 5, magnetic fields can be represented by lines, called **magnetic field lines**, and we saw the magnetic field lines around a bar magnet and a solenoid.

## Magnetic flux

### Definition

**Magnetic flux** is defined as the number of magnetic field lines passing through an imaginary area.

Mathematically, if the magnetic field is perpendicular to the area, then the magnetic flux is equal to the product of strength of the magnetic field and size of the area as shown in Figure 6.4 (a):

$$\varphi = \boldsymbol{BA},$$

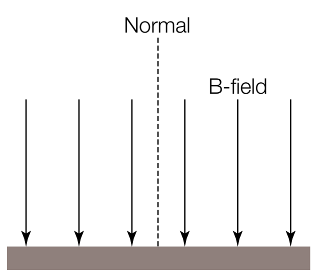
where $\varphi$ is the magnetic flux in webers (Wb), $\boldsymbol{B}$ is the magnetic field strength in Tesla (T), and $A$ is the area in $m^2$.

However, if the magnetic field lines are not perpendicular to the area, then only the perpendicular component of the magnetic field is taken into consideration. In these cases:

$$\varphi = \boldsymbol{BA}\cos\theta,$$

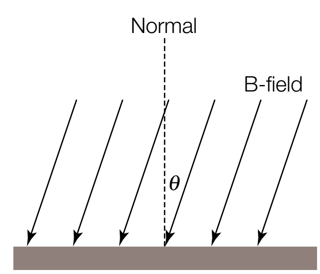
where $\varphi$ is the magnetic flux in Wb, $\boldsymbol{B}$ is the magnetic field strength in T and $A$ is the area in $m^2$. $\theta$ is the angle between the magnetic field lines and the *normal* to the area (see Figure 6.4b).

**NOTE:** $\theta$ is *not* the angle between the magnetic field line and the area.



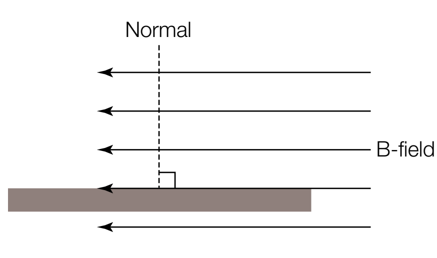

Field lines $\perp$ to the area
$\theta = 0°$, $\cos\theta = 1$
$\Phi$ is a maximum

**Figure 6.4 (a)** Magnetic flux, field lines perpendicular




Field lines incline to the plane
$0° < \theta < 90°$, $\cos\theta < 1$
$\Phi$ is below the maximum

**Figure 6.4 (b)** Magnetic flux, field lines inclined




Field lines // to the area to the area plane $\theta$
$\theta = 90°$, $\cos\theta = 0$
$\Phi$ is a minimum

**Figure 6.4 (c)** Magnetic flux, field lines parallel

**ANALOGY:** The magnetic flux can be compared to the number of arrows that can be collected by a wooden shield, which of course depends on the number of arrows being fired (the magnetic field strength) and the area of the shield. It also depends on the angle at which the shield is facing the arrows. If the shield is held perpendicular to the arrows (in which case θ is zero), then the number of arrows collected (flux) is the maximum. If the shield is held at an angle to the arrows, then the number collected will be below the maximum. Last, if the shield is held parallel to the arrows, then the shield cannot collect any arrows.

**Example**

A loop of wire is circular in shape, and has a radius of 4.0 cm. If there is a magnetic field with a strength of 0.50 T passing through the coil perpendicular to the loop, calculate the magnetic flux for this loop. If the loop is rotated through an angle of 30°, what is the new magnetic flux?

**Solution**

(a) $\varphi = \boldsymbol{B}A\cos\theta$

$\boldsymbol{B} = 0.50$

$A = \pi \times 0.040^2$

$\theta = 0°$

$\varphi = 0.50 \times \pi \times 0.040^2 \times \cos 0°$

$\approx 2.51 \times 10^{-3}$ Wb

(b) $\varphi = \boldsymbol{B}A\cos\theta$

$\boldsymbol{B} = 0.50$

$A = \pi \times 0.040^2$

$\theta = 30°$

$\varphi = 0.50 \times \pi \times 0.040^2 \times \cos 30°$

$\approx 2.18 \times 10^{-3}$ Wb

## Magnetic flux density

Since we know that $\varphi = \boldsymbol{B}A$, if we re-arrange this formula, then:

$$\boldsymbol{B} = \frac{\varphi}{A}$$

According to this equation, we can define the magnetic field strength $\boldsymbol{B}$ in another way:

**Definition**

A magnetic field, $\boldsymbol{B}$, can be defined as the amount of magnetic flux per unit area, or simply the **magnetic flux density**.

It follows that if the unit for φ is the Wb, and the unit for A is metres squared, $\boldsymbol{B}$ must have the unit weber/metre squared (Wb m$^{-2}$). Hence the unit of magnetic field can be either T (Tesla) or Wb m$^{-2}$.

# 6.3 Faraday's law: a quantitative description of electromagnetic induction

- ***Describe generated potential difference as the rate of change of magnetic flux through a circuit***

Faraday's law states: The size of an induced EMF is directly proportional to the rate of change in magnetic flux.

Mathematically:

$$\varepsilon = \frac{\Delta\varphi}{\Delta t} \text{ (this is not required by the syllabus)}$$

When there are $n$ turns in the coil, the formula becomes:

$$\varepsilon = n\frac{\Delta\varphi}{\Delta t}$$

Where $n$ is the number of turns, $\varphi$ is the magnetic flux in Webers, $t$ is the time in seconds, and $\frac{\Delta\varphi}{\Delta t}$ is the rate of change in flux.

Consequently, we need to modify our early definition: instead of *In order to induce electricity, a changing magnetic field is essential*, we need:

In order to induce an EMF, a changing magnetic flux is essential.

**NOTE:** A changing magnetic field will result in a changing magnetic flux; however, there are other ways to create changes in magnetic flux.

## Factors that determine the size of the induced EMF

From the equation above, we can clearly see the factors that will affect the size of the induced EMF:

1. *The size of the change in the magnetic field.* As the size of the change in the magnetic field increases, the size of the induced EMF increases.
2. *The speed of the relative motion between the magnetic field and the conductor.* As the speed increases, the rate of change in flux increases, hence the size of the induced EMF increases.
3. *The number of turns of coil or conductors.* Increasing the number of turns in the coil will increase the size of the induced EMF.
4. *The change in area that the magnetic field passes through.* The greater the change in area, the greater the change in the flux value, so the size of the induced EMF increases.

**NOTE:** Sometimes for a single moving conductor, the idea of 'cutting' the field lines is used as the conductor moves through the magnetic field, to denote that the conductor is linking with the magnetic field and so there exists a changing magnetic flux. A maximum 'cut' by convention means a maximum change in flux.

## The negative sign

It is more correct for Faraday's law of electromagnetic induction to have a negative sign, that is:

$$\varepsilon = -n\frac{\Delta\varphi}{\Delta t}$$

The reason for having a negative sign as well as its significance on the results of the electromagnetic induction will be discussed in the section 'Lenz's law'.

**Example**

Consider a rectangular coil with dimensions 5.0 cm × 4.0 cm placed between the poles of two bar magnets that generate a field strength of 0.60 T. The coil has 200 turns, and is initially parallel to the field lines. If the coil is made to rotate anti-clockwise to reach the vertical position in 0.010 second, calculate the EMF generated in the coil.

**Solution**

Note that when the coil is parallel to the magnetic field, the flux is a minimum ($\theta = 90°$), whereas when the coil is at the vertical position, the flux is at its maximum ($\theta = 0°$).

$$\varepsilon = -n\frac{\Delta\varphi}{\Delta t}$$

$$n = 200$$

$$\begin{aligned}\Delta\varphi &= \text{final } \varphi - \text{initial } \varphi \\ &= 0.60 \times 0.050 \times 0.040 \times \cos 0° - 0.60 \times 0.050 \times 0.040 \times \cos 90° \\ &= 1.2 \times 10^{-3}\ \text{Wb}\end{aligned}$$

$$\Delta t = 0.010$$

$$\begin{aligned}\varepsilon &= -\frac{200 \times 1.2 \times 10^{-3}}{0.010} \\ &= -24\ \text{V}\end{aligned}$$

**NOTE:** This type of calculation is not required by the syllabus. It is shown here to demonstrate the application of Faraday's law.

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Simulation: Faraday's law

## 6.4 Lenz's law

■ ***Account for Lenz's law in terms of conservation of energy and relate it to the production of back EMF in motors***

**Lenz's law states**

Whenever an EMF is being induced in a conductor as a result of changing magnetic flux, the direction of the induced EMF will be such that the current it produces will give rise to a magnetic field that always opposes the change and hence opposes the cause of induction.

Therefore, the negative sign in Faraday's law assigns the direction for the induced EMF, that is, it opposes the cause of induction.

**Example 1**

Determine the direction of the induced EMF and hence the current in the coil for the following situations:

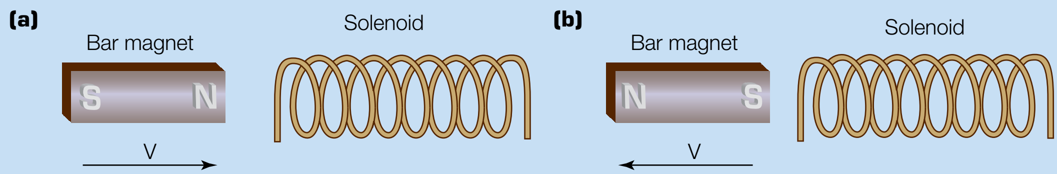



**Figure 6.5** Lenz's law examples

### Solutions

(a) The magnet is moving relative to the coil, hence there is a changing magnetic field, therefore induction. The induced EMF or current will flow to *oppose* the cause of induction, that is, the north pole moving towards the coil. To oppose this approaching north pole, the current will flow in a direction that will result in a north pole on the left hand side of the coil.

**NOTE:** North and north repel.

Use the right-hand grip rule: the thumb points to the left, therefore the current flows into the coil on the right and out on the left.

(b) To oppose the receding south pole, a north pole needs to be created on the left hand side of the coil.

**NOTE:** To attract the south pole back.

Hence, using the right-hand grip rule, the current flows into the coil on the right and out on the left.

### Example 2

A circular loop of wire is situated in a magnetic field as shown in the diagram below:

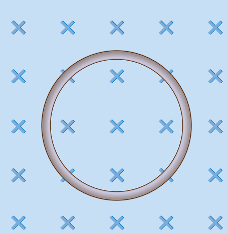


**Figure 6.6** Lenz's law example 2

(a) At this instant, will there be a current flowing in the loop?
(b) If the magnetic field increases in strength in the direction shown in the diagram, what will happen in the loop?

### Solutions

(a) No current will be flowing in the loop, since there is no change of magnetic field or flux.
(b) There will be a current flowing in the loop. The direction of current is anti-clockwise. To oppose an increase in the strength of the magnetic field

into the page, the induced current must flow in such a way as to produce a magnetic field out of the page. This means that the current should produce a north pole pointing out of the page. By applying the right-hand grip rule, the thumb points out of the page and the fingers curl anti-clockwise; hence, the current flows anti-clockwise.

### Example 3

Determine the direction of the induced current in a moving wire for the following cases (assume the circuit is completed externally):

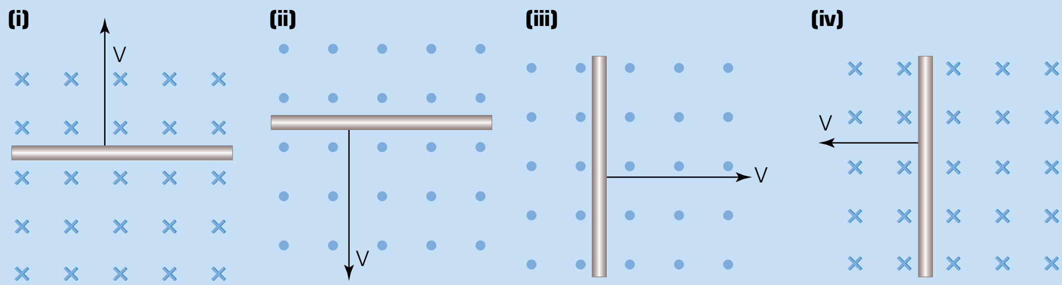



**Figure 6.7 (a)**

### Solution

Since the cause of the changing magnetic flux is the velocity of the wire (the relative motion between the wire and the magnetic field), the induced current will flow in such a way that it will oppose this velocity. Hence the force created by the induced current will have the opposite direction to that of the velocity.

**NOTE:** The force is trying to stop the movement.

Hence by applying the 'right-hand palm rule', if we point the palm (the force) in the opposite direction to the velocity of the wire, and align the fingers with the magnetic field, the thumb will point to the direction of the induced current.

**NOTE:** Also note that for all the cases, the conductor is 'cutting' the magnetic field lines maximally (perpendicularly), so the change in flux is maximal. This results in a maximum induced EMF or current.

Therefore:

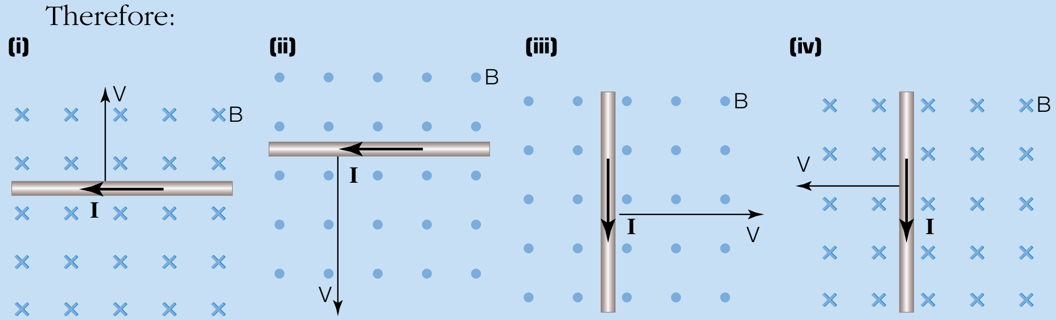



**Figure 6.7 (b)**

# 6.5 Lenz's law and the conservation of energy

Consider a wire that is moving through a magnetic field directed into the page in a vacuum. The wire initially has a constant velocity $\boldsymbol{v}$.

As the wire moves through the magnetic field, it will experience a changing magnetic flux. (The wire as it moves carves out a changing area that links up with the magnetic field, therefore the magnetic flux changes.) Hence there will be an EMF induced and if we assume there is a complete external circuit, a current will flow.

If the current did not flow in the direction to oppose the cause of induction, that is, the velocity of the wire as stated by Lenz's law, but rather flowed in the opposite direction, then the wire would speed up rather than slow down. This will in turn create a greater changing magnetic flux, and in turn induce a greater EMF or current. This induced current will further speed up the wire, inducing an even greater EMF or current. As this cycle goes on, eventually, the wire would be moving at an infinitely high speed (limited to *c*), and there would be an infinitely large current flowing in the wire. Since no energy input is required in this case, energy is being created! This of course *cannot* happen, since the **law of conservation of energy** states: Energy cannot be destroyed or created, it can only be transformed or transferred. Hence to obey the law of conservation of energy, the current *must* flow to oppose the cause. Therefore, Lenz's law is just an example of the conservation of energy.

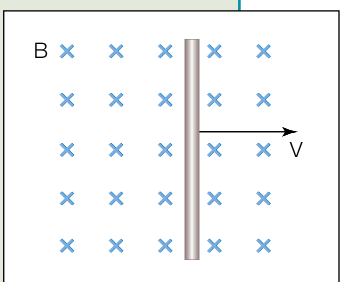



**Figure 6.8**
Lenz's law and the conservation of energy

It follows that as the wire moves through the magnetic field, current will flow, the motion of the wire will be opposed due to Lenz's law, and if there is no external force to move it, it will slow down. As the wire slows down and eventually comes to rest, the induced current will reduce in size and eventually drop to zero. Hence to maintain a constant production of current, force must be applied to maintain the motion of the wire. Thus work or mechanical energy is applied and is converted into electrical energy through electromagnetic induction; no energy is created or destroyed! This forms the basis of electric generators, which will be discussed in Chapter 7.

Remember, there is no free lunch!

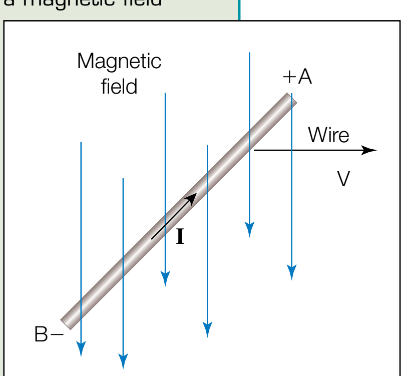
# 6.6 The need for external circuits

Again, consider a wire with an initial velocity $\boldsymbol{v}$ that is moving through a magnetic field directed downwards.

Since the wire is moving through the magnetic field, a changing flux will be experienced and an EMF will be induced. By applying the right-hand palm rule, one can deduce that the induced EMF will cause a current to flow into the page (towards A). Although conventional current may appear to be a stream of moving positive particles moving towards A, in fact the current is created by electrons flowing in the opposite direction; hence, we know that the electrons will move towards B.

The migration of the electrons will make terminal B negative and the lack of electrons will make terminal A positive. This build up of charge will act to resist further flow of electrons. Momentarily later, the electrostatic force will be in equilibrium with the induced EMF and the migration of the charges will stop. Current stops flowing even though the EMF is still being induced due to the motion of the wire.

**Figure 6.9**
A conductor moving through a magnetic field



**ANALOGY:** A battery sitting by itself has an EMF or voltage, but will not have any current flow.

However, when the terminals A and B are connected via a long wire outside the magnetic field (the external circuit), the circuit will be completed. Electrons will be able to move out from terminal B and back to fill the electron deficiency at A. Consequently, a continuous flow of current is established. Also note that through the **external circuit**, current flows from A to B, that is, from the positive terminal to the negative.

Also, it is very important to note that at least part of the external circuit must be outside the magnetic field. Otherwise, it will be no different to the isolated wire without an external circuit.

To conclude, even if there is an EMF induced, if there is no external circuit, there will only be a momentary flow of current that will then stop.

### Example 1

Consider the situation shown in Figure 6.9. If there is no external circuit connecting terminals A and B, describe the subsequent motion of the wire.

**Solution**

As the wire moves through the magnetic field, an EMF will be induced. This will cause a current to flow from B to A. By applying the right-hand palm rule, the force acting on the wire will be to the left. This will result a deceleration of the wire and the wire will slow down. However, due to the lack of the external circuit, momentarily later, current will stop flowing. The deceleration force will disappear and the subsequent motion is that the wire will continue moving at a constant velocity to the right after a brief moment of deceleration.

**NOTE:** Conventional current flows from the positive terminal to the negative terminal in an external circuit, but from negative to positive inside the power source, such as within the wire in Figure 6.9.

### Example 2

A rectangular loop of wire is moving through a magnetic field as show below:

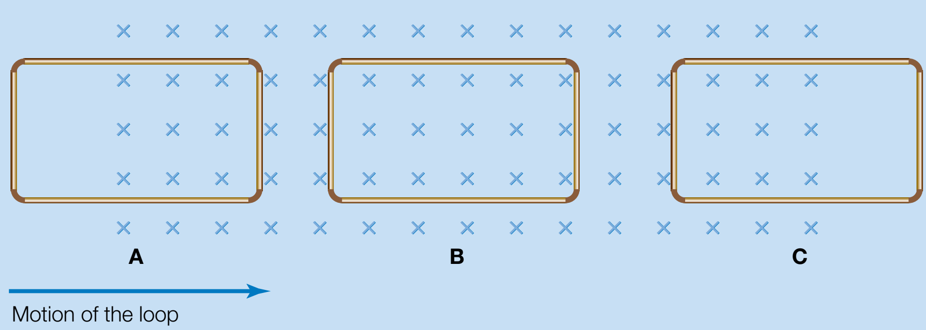



**Figure 6.10** A rectangular loop moving through a magnetic field directed into the page

Describe the flow of current in the loop when the loop is at positions A, B and C.

**Solution**

First, we have to note that for all three positions, the top and bottom portion of the rectangular loop never 'cut' the magnetic field. Hence they have no role in the electromagnetic induction and consequently can be neglected.

*At position A*: The right portion of the loop is subject to a changing magnetic field (cutting the field lines). We point our palm to the left, opposite to the direction of the motion of the coil, and fingers into the page and the current (thumb) is up. Hence the current flows anti-clockwise.

*At position B*: A similar approach can be used. Both left and right portions have current flowing upwards. Therefore, they will cancel each other; no current will flow in the loop.

**NOTE:** This is what happens if the external circuit is inside the magnetic field.

*At position C*: The left portion is subject to a changing magnetic field. Similarly, we can determine that the current is up. Hence the current flows clockwise in the loop.

## 6.7 Another application of Lenz's law: back EMF in DC motors

### ■ *Explain that, in electric motors, the back emf opposes the supply emf*

When the coil of a DC motor is spinning inside the magnetic field, at the same time, the coil is subject to a changing magnetic field caused by the relative motion between the coil and the field. This changing magnetic flux will induce an EMF in the coil. As a consequence of Lenz's law, the induced EMF will cause the current to flow in such a way that it will oppose the cause of induction—the rotation of the coil. Hence the induced current will flow in the opposite direction to the input current, thus limiting the size of the input or forward current. This will decrease the torque, slowing down the rotation of the motor. Since the induced EMF works against the input voltage, it is referred to as the **back EMF**.

When a DC motor is switched on, its rotational motion does not reach the maximum instantaneously due to its inertia; instead it starts off from rest and builds up its speed to the maximum quite rapidly. When the rotational speed is low, the coil is subject to a small rate of change in magnetic flux, so the back EMF induced is also small. Small back EMF results in almost no opposition to the forward EMF or current, which is useful in creating a large torque to accelerate the rotation. The drawback is that at this time, the large current may burn out the coil. To partially limit the size of the current, a device called a **starting resistance** may be employed. This is a resistive load that is connected in series with the coil when the motor is starting off. By increasing the resistance, it is able to reduce the forward current, thus protecting the coil from burning out.

As the rotational speed of the coil increases, the rate of change in magnetic flux also increases, so the size of the back EMF increases. This limits the forward EMF so that the starting resistance can be removed. Soon after, the back EMF will achieve equilibrium with the forward EMF. At this stage, the motor is rotating at its working speed and will maintain a constant velocity thereafter, since the back EMF limits the forward EMF so that the net current produces torque just large enough to balance the friction and the load on the motor.

## Eddy currents

# 6.8

### ■ *Explain the production of eddy currents in terms of Lenz's law*

As we have discussed, whenever there is a changing magnetic field or magnetic flux, EMF will be induced. The EMF will cause a current to flow in a wire provided there is an external circuit. Quite differently, in the case of a **solid conductor**, the EMF will cause loops of current to flow, and these circular currents are referred to as **eddy currents**. (Eddy = circle, loop.)

Eddy currents flow in solid conductors.

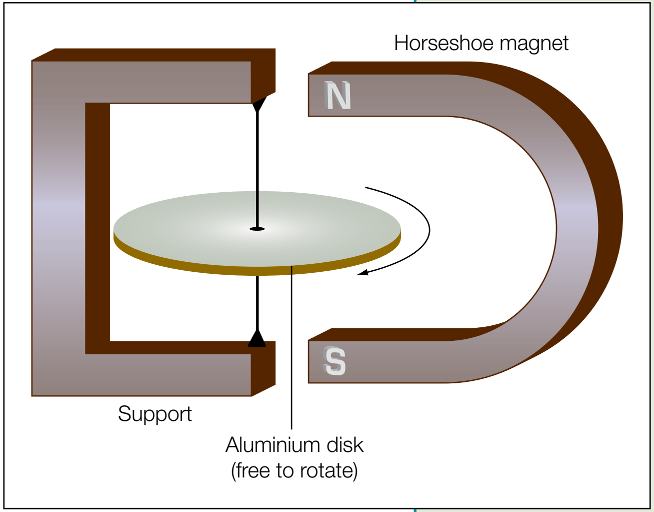



**Figure 6.11 (a)** A spinning aluminium disk

The induced eddy currents also follow Lenz's law, that is, they circulate in such a way as to oppose the cause of induction. This principle is illustrated in Figure 6.11.

**NOTE:** Eddy currents are not 'new' things, they are simply circulating currents.

**Figure 6.11 (b)** A spinning aluminium disk

As shown in Figure 6.11, if a freely rotatable aluminium disk is spun, it will rotate for quite a while before it comes to rest. However, when a horseshoe magnet is brought next to it, the disk spins for a much shorter time and comes to rest much more quickly. The explanation for this phenomenon is that as the horseshoe magnet is brought next to this rotating disk, the disk is made to spin inside the magnetic field, so the disk experiences a changing magnetic field. Consequently, eddy currents are induced in the disk. These eddy currents follow Lenz's law and circulate to generate a magnetic field to oppose the cause of induction, that is, the spinning motion of the disk. Hence, the disk is brought to rest very promptly.

Consider what will happen to this disk if slots are cut in it, or it is replaced by a plastic disk. The answer is simple: the disk will spin as fast and as long as without the horseshoe magnet. This is because cutting slots and plastic itself (being an insulator) will impede the flow of eddy currents, so the effect of eddy currents is minimised.

**NOTE:** The detailed flow pattern of eddy currents is not required by the syllabus.

# Applications of induction and eddy currents

**SECONDARY SOURCE INVESTIGATION**

**PFAs**

H3

**PHYSICS SKILLS**

H13.1A, B, C, E
H14.1D, G, H
H14.3D

## Induction cooktop

- ***Gather, analyse and present information to explain how induction is used in cooktops in electric ranges***

Induction cooktops use a changing magnetic field to generate eddy currents in order to produce the heat that cooks the food. The schematic diagram of an induction cooktop is shown in Figure 6.12.

The functional principle of the induction cooktop is as follows. When an AC current flows through the coil, the changing current produces a changing magnetic field. This magnetic field passes through the ceramic cooktop and the saucepan or any other metal containers. Within the saucepan's base, eddy currents are generated. The circulation of eddy currents in the presence of the resistance in the saucepan generates heat. This heat can be used to heat the food content.

**NOTE:** A current flowing through any conductor that has resistance will generate heat.

The advantages of this type of cooktop over others are:

- They are very efficient in converting electrical energy to heat energy compared to normal electric cooktops that rely on conduction. The source of heat is in direct contact with the food being cooked.
- There is no open fire so it reduces the possibility of a fire hazard in the kitchen (unlike gas cooking).
- The ceramic cooktop is very easy to clean, so it improves hygiene maintenance.
- The cooktop itself does not generate heat, so burns to children are less likely.

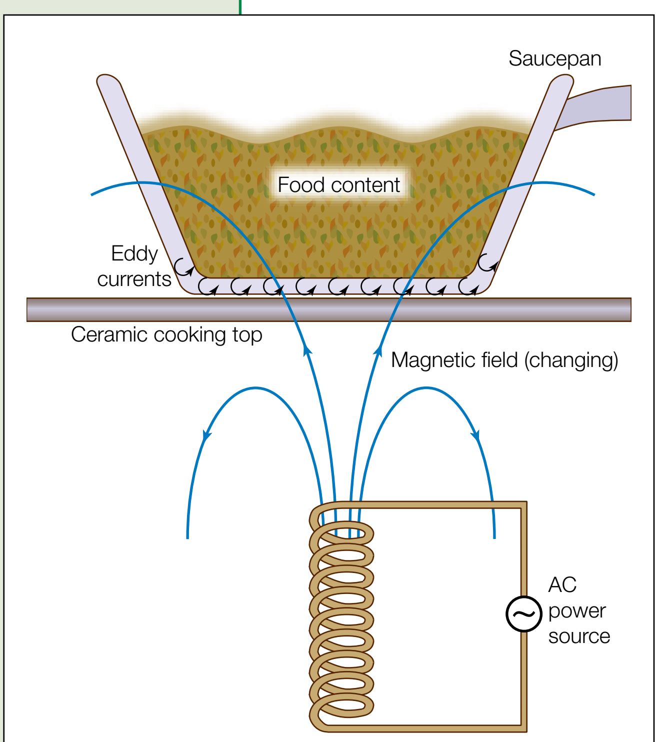



**Figure 6.12**
Induction cooktop

Induction cooktops only heat up in contact with metal. Notice how the ice cubes have barely melted.

## Eddy current braking

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H13.1A, B, C, E
H14.1D, G, H
H14.3D

### ■ *Gather secondary information to identify how eddy currents have been utilised in electromagnetic braking*

As discussed, a rotating disk in the presence of a magnetic field will be brought to rest much more promptly than without the magnetic field. This principle is used in braking.

Using a train as an example, suppose a train wants to stop; very powerful magnets are lowered down next to the metal wheels of the train. The rotating wheels in the presence of the magnetic field slow down very rapidly due to the production of eddy currents within the wheels that oppose the motion of the wheels as described above. It is important to note that the braking effect reduces as the speed of the train decreases. This is because the size of the eddy currents, and therefore of the force that opposes the motion of the wheels, is proportional to the rate of change in magnetic flux (Faraday's law) which consequently depends on the relative motion between the wheels and the external magnets. Hence, when the train reaches very low speeds, eddy current braking is no longer useful and at that point a mechanical brake is applied to stop the train completely.

The advantages of this type of braking are:

- It is smooth—the braking force is greatest when the train is at its operating speed, but gradually becomes smaller to an unnoticeable force as the train slows down.
- There is no wear and tear as there is no physical contact between the braking system and the wheels. Consequently, there is a low maintenance effort and cost.

The main problem with this system is that it only works for metal wheels and at higher speeds.

Eddy current braking

## Electromagnetic induction

FIRST-HAND INVESTIGATION

PFAs

H1, H3

PHYSICS SKILLS

H12.1A, D
H12.2B
H12.3D
H13.1E
H14.1A, D, G

### ■ *Perform an investigation to model the generation of an electric current by moving a magnet in a coil or a coil near a magnet*

An interesting class activity can be used here prior to commencing this investigation, as follows:

- Connect the ends of a long (approximately 40 m) wire to the terminals of a galvanometer.
- Run a section (about 18 m) of this wire in an east–west direction.
- Have two students spin this east–west section of wire like a skipping rope, while other students observe the galvanometer.
- When the wire moves up, the galvanometer moves in one direction, and then in the opposite direction as the wire moves down.
- The amount of deflection of the galvanometer can be increased by increasing the speed of the 'skipping rope'.

Students should acknowledge that, as the resistance of the wire is constant, the current shown by the galvanometer is proportional to the EMF generated in the wire as it moves through Earth's magnetic field (Ohm's law).

TR

Risk assessment matrix

# The effects of magnets on electric currents

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H11.1A, B, E
H11.2A, B, C, E
H11.3A, B
H12.1A, D
H12.2B
H13.1C
H14.1A, D, G
H14.3C

TR

Risk assessment matrix

- ***Plan, choose equipment or resources for, and perform a first-hand investigation to predict and verify the effect on a generated electric current when:***
  - ***the distance between the coil and magnet is varied***
  - ***the strength of the magnet is varied***
  - ***the relative motion between the coil and the magnet is varied***

**NOTE:** This procedure requires you to plan the experiment, including selecting appropriate equipment. A discussion of what apparatus is available would be beneficial before commencing this investigation.

## Topics

1. Demonstrate the production of electricity by using a moving magnet and coil.
2. Demonstrate the effect of following on the generation of electricity using a moving magnet and coil:
   (a) the distance between the magnet and coil is changed
   (b) the strength of the magnet is changed
   (c) the relative motion between the coil and magnet is changed

## Aim

A suitable aim for the investigation should be written, using the syllabus points as a guide. (The syllabus point actually provides the aim in this case.)

## Hypothesis

An educated prediction of what will happen in each of the situations should be made using the theory of electromagnetic induction.

## Apparatus

A straightforward list of required equipment should include a sensitive galvanometer or microammeter, as the generated current is quite small. The strongest magnets available should be used.

A lab shot of the apparatus

## Method

Clear, step-wise instructions should be written that will enable another reader to reproduce the experiment as it was performed. Diagrams should be drawn to illustrate what was done.

The set up of both experiments may follow the one shown in Figure 6.3. It is important to emphasise that when doing the second experiment, *only one* variable can be changed a time and the others need to be kept as the **controls**. This idea is demonstrated in the chapter exercise questions.

## Results and observations

This is where the outcome of the above method is recorded carefully. In this experiment, qualitative results are sufficient, that is, the actual current generated does not matter, but the effect on the current does.

## Discussion

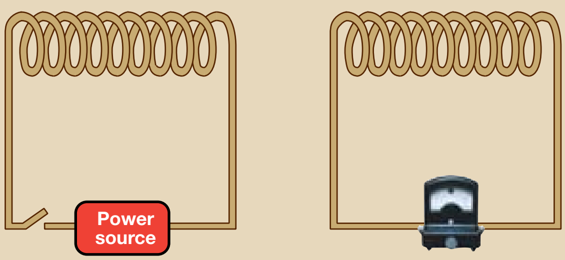
Discuss the reliability (repeatability) of the experiment and the validity (correctness) of the results. Ways to improve the experiment should be noted here too.

## Conclusion

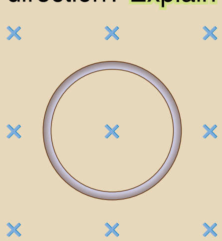
A brief summing up of the experiment's success or otherwise is made here.

# CHAPTER REVISION QUESTIONS

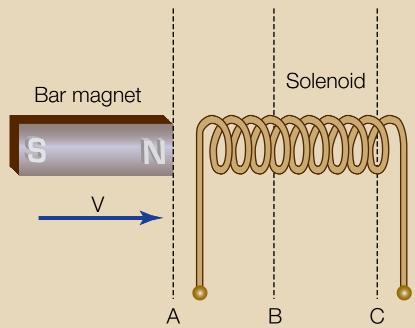
1. Outline the procedure of Faraday's mutual induction experiment, and describe the findings and theory of this experiment.
2. Two identical solenoids are placed next to each other as shown in the figure below.




   (a) Explain why, when a DC current is switched on in the primary coil, there is a flickering movement of the needle of the galvanometer connected to the secondary coil.
   (b) What manoeuvre can be used so that a current is always registered by the galvanometer in the secondary coil?
   (c) Explain the phenomenon of the flickering becoming much larger when a soft iron core is inserted inside the secondary coil.
3. A circular loop of coil is placed inside a magnetic field as shown in the figure below. If now the coil is stretched to form a square, will there be an EMF induced and what is its direction? Explain your answer.

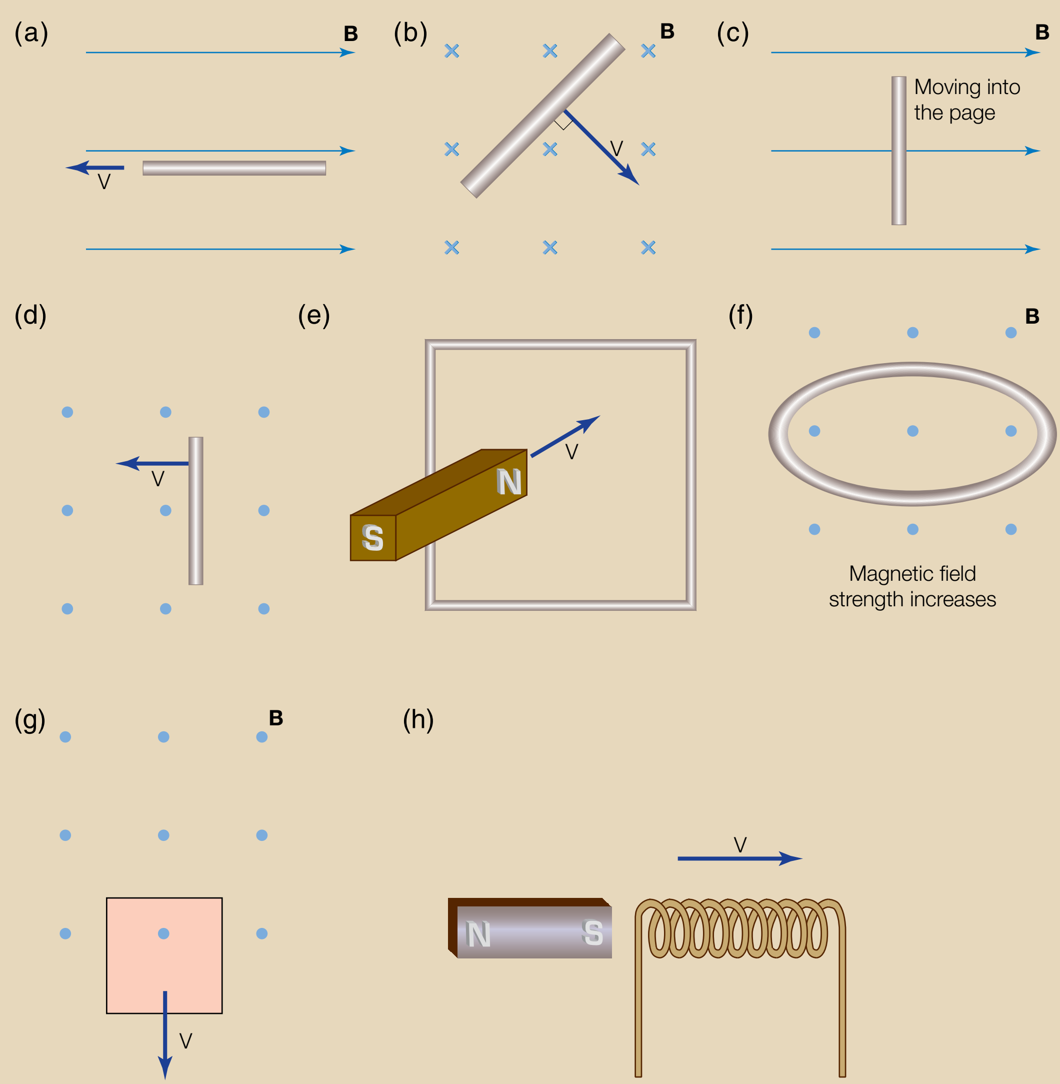


4. A bar magnet is moved from point A towards a solenoid to point B at a constant speed (V).
   (a) Describe what will occur in the solenoid.
   Describe the change to the size of the induced EMF if:

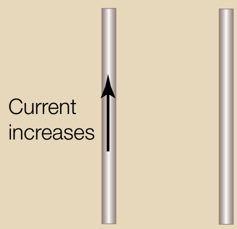



(b) The magnet is moved from A to B at a doubled speed, that is, 2 V.
(c) The magnet is moved from A to C at V, such that AC is twice as long as AB.
(d) The magnet is changed to one which is twice as weak.
(e) The south pole faces the solenoid.
(f) The number of turns of the solenoid is increased by 10 times.

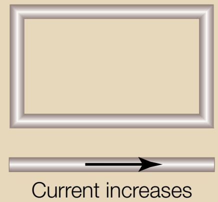
5. Use Faraday's law and Lenz's law to determine the direction of the induced current for the following conductors (the thicker lines):



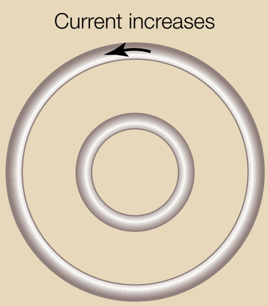
(i)



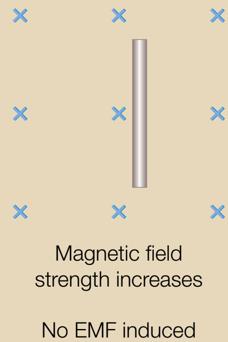

(j)




(k)




(l)




6. Lenz's law is an extension of the law of conservation of energy. Discuss this statement.

7. A small magnet is projected horizontally towards a solenoid at a constant velocity. Assume there is no friction. Describe the motion of the magnet when:
   (a) the ends of the solenoid are not connected.
   (b) the ends of the solenoid are connected via a long wire.
   (c) the solenoid has its ends connected and a soft iron core is placed inside the solenoid.

8. (a) Back EMF limits the speed of electric motors. Discuss the principle behind this statement.
   (b) Using the idea of back EMF, explain why an electric drill, when jammed in a wall, is very likely to burn out if it is not switched off immediately.

9. A small magnet is dropped vertically through an infinitely long hollow copper tube.
   (a) Describe what will occur in the copper tube as the magnet falls.
   (b) Sketch a graph to describe the change in the velocity of the magnet as a function of time.
   (c) If the copper tube has numerous holes in its wall, will this change the answer to part (b)?

10. Eddy currents can be beneficial sometimes, whereas at other times, they have adverse effects.
    (a) Describe two situations where eddy currents are beneficial.
    (b) Describe one situation where eddy currents are a nuisance to the system.

11. What consideration(s) should be made when one is to choose cooking wares that are to be used with an induction cooktop?

12. Describe the principle of eddy current braking and evaluate its advantages.

13. Design an experiment that demonstrates how the strength of the magnetic field will influence the size of the induced EMF.

SR

Answers to chapter revision questions