TOPIC 5
The Motor effect

5.1 Overview

5.1.1 Module 6: Electromagnetism

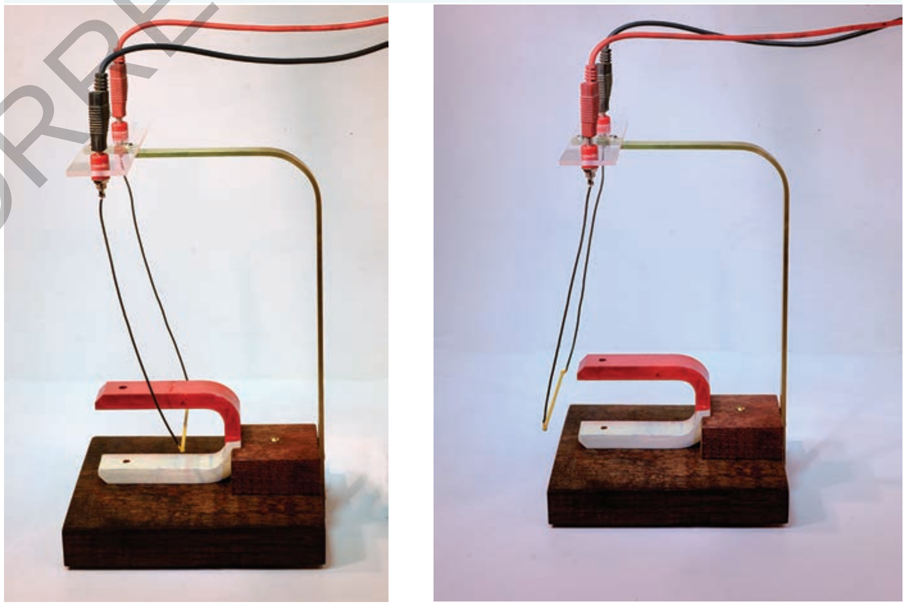
The Motor effect

Inquiry question: Under what circumstances is a force produced on a current-carrying conductor in a magnetic field?

Students:

- investigate qualitatively and quantitatively the interaction between a current-carrying conductor and a uniform magnetic field ($\boldsymbol{F} = \boldsymbol{BI}l\sin\theta$) to establish: (ACSPH080, ACSPH081)
  - conditions under which the maximum force is produced
  - the relationship between the directions of the force, magnetic field strength and current
  - conditions under which no force is produced on the conductor
- conduct a quantitative investigation to demonstrate the interaction between two parallel current-carrying wires
- analyse the interaction between two parallel current-carrying wires $\left(\frac{F}{l} = \frac{\mu_0}{2\pi} \times \frac{I_1 I_2}{r}\right)$ and determine the relationship between the International System of Units (SI) definition of an ampere and Newton's Third Law of Motion (ACSPH081, ACSPH106)

FIGURE 5.1 (a) A conductor is arranged as a swing, in a magnetic field (red is north). A current flows in the conductor and creates a magnetic field that interacts with the permanent magnetic field. (b) What change could have been made to the experiment to make the conductor swing in the opposite direction?



(a) (b)

5.2 Magnetic fields

5.2.1 Current-carrying conductors and magnetic fields

What would your life be like without electricity? Modern industrialised nations are dependent on electricity. Electricity is easy to produce and distribute, and is easily transformed into other forms of energy. Electric motors are used to transform electricity into useful mechanical energy. They are used in homes, for example in refrigerators, vacuum cleaners and many kitchen appliances, and in industry and transport.

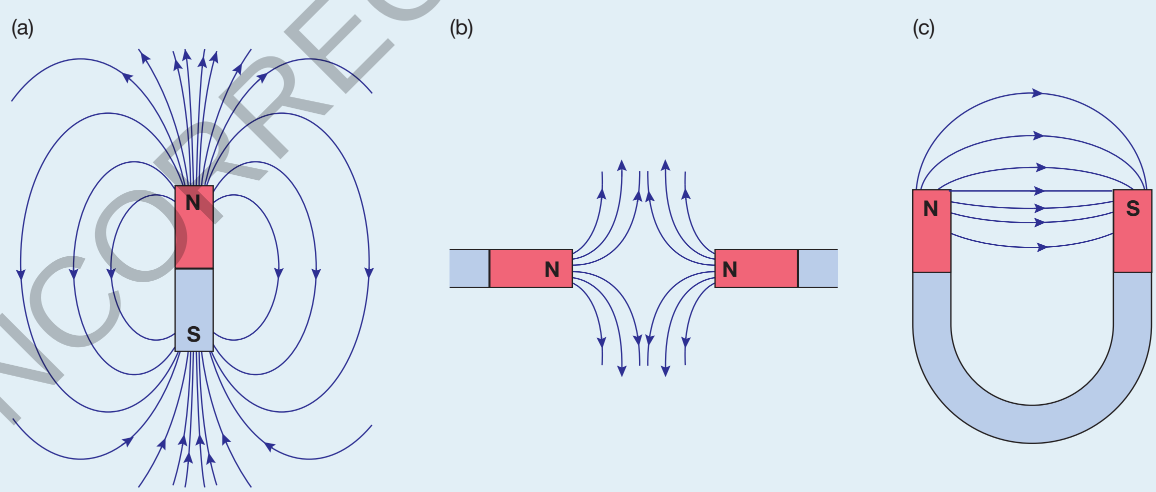
Use the box below to revise your work on magnetic fields. This material is fundamental to the understanding of how DC electric motors operate.

PHYSICS IN FOCUS

Review of magnetic fields

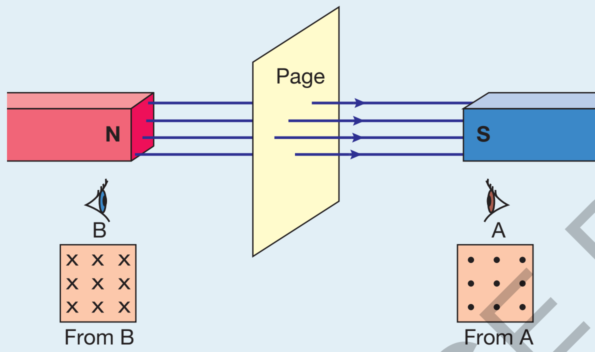
- The law of magnetic poles states that opposite poles of magnets attract each other and like poles of magnets repel each other.
- Magnetic fields are represented in diagrams using lines. These show the direction and strength of the field. The density of the field lines represents the strength of the magnetic field. The closer the lines are together, the stronger the field.
- The direction of the magnetic field at a particular point is given by the direction of the force on the N pole of a magnet placed within the magnetic field. It is shown by arrows on the magnetic field lines.
- Magnetic field lines never cross. When a region is influenced by the magnetic fields of two or more magnets or devices, the magnetic field lines show the strength and direction of the resultant magnetic field acting in the region. They show the combined effect of the individual magnetic fields.
- The spacing of the magnetic field lines represents the strength of the magnetic field. It follows that field lines that are an equal distance apart represent a uniform magnetic field.
- Magnetic field lines leave the N pole of a magnet and enter the S pole.
- The following diagrams in figure 5.2 represent the magnetic fields around (a) a single bar magnet, (b) two N poles close to each other, and (c) a horseshoe magnet.

FIGURE 5.2 Magnetic field lines for (a) a single bar magnet, (b) two *N* poles close to each other and (c) a horseshoe magnet



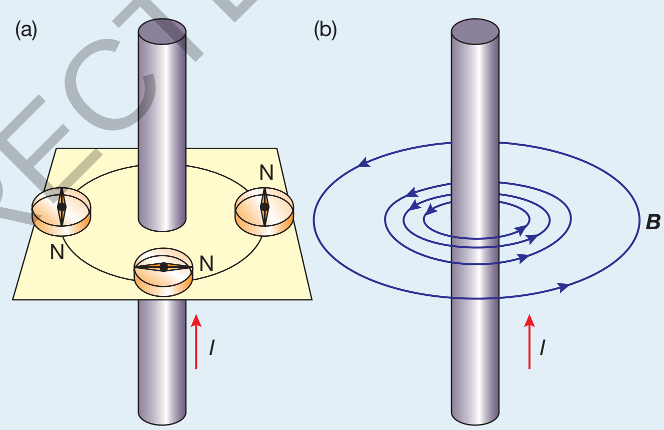
- In a diagram, as seen in figure 5.3, magnetic field lines going out of the page are represented using dot points ($\cdot$). This is like an observer seeing the pointy end of an arrow as it approaches.
- Magnetic field lines going into the page, also seen in figure 5.3, are represented using crosses ($\times$). This is as an archer would see the rear end of an arrow as it leaves the bow.

FIGURE 5.3 Magnetic field lines coming out of the page as observed by *B* and going into the page, as observed by *B*



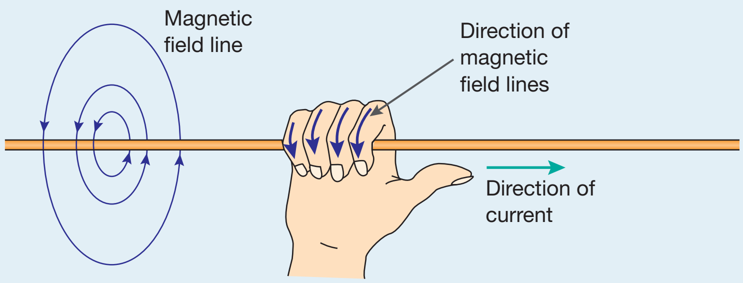
- The movement of charged particles, as occurs in an electric current, produces a magnetic field. The magnetic field is circular in nature around the current-carrying conductor, as shown in figure 5.4, and can be represented using concentric field lines. The field gets weaker as the distance from the current increases.

FIGURE 5.4 (a) Compasses can be used to show the circular nature of the magnetic field around a straight current-carrying conductor. (b) The magnetic field is circular and stronger closer to the wire.



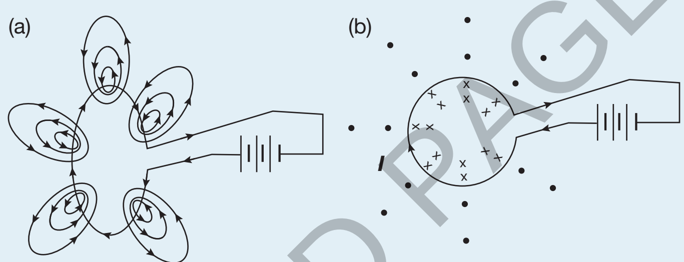
- The direction of the magnetic field around a straight current-carrying conductor is found using the right-hand grip rule, as shown in figure 5.5. When the right hand grips the conductor with the thumb pointing in the direction of conventional current, the curl of the fingers gives the direction of the magnetic field around the conductor.

FIGURE 5.5 The right-hand grip rule



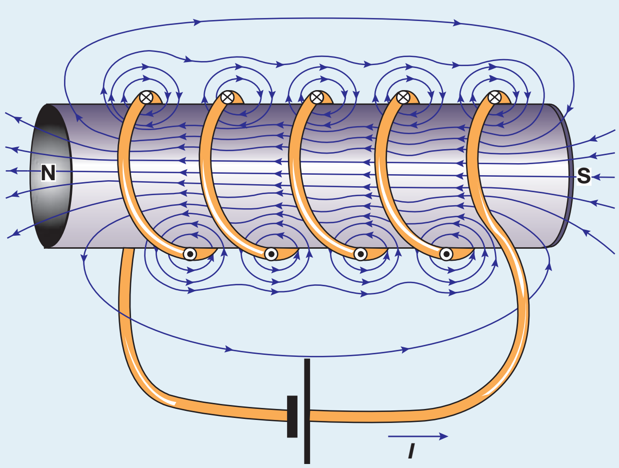
- When a current-carrying conductor is bent into a loop, the effect is to concentrate the magnetic field within the loop, as shown in figure 5.6.

FIGURE 5.6 The magnetic field of a loop (a) 3-D representation (b) 2-D representation



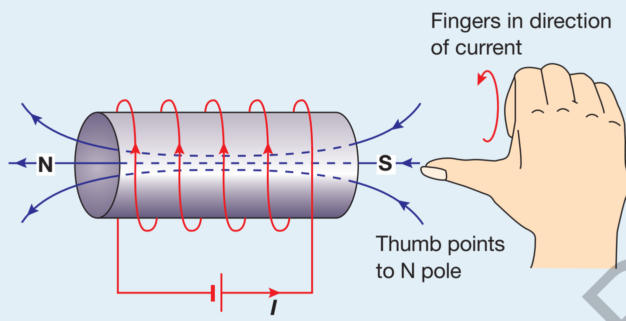
- A **solenoid** is a coil of insulated wire that can carry an electric current and is shown in figure 5.7. The number of times that the wire has been wrapped around a tube to make the solenoid is known as the number of 'turns' or 'loops' of the solenoid. The magnetic fields around each loop of wire add together to produce a magnetic field similar to that of a bar magnet. Note that the magnetic field goes through the centre of the solenoid as well as outside it.

FIGURE 5.7 The magnetic field around a current-carrying solenoid



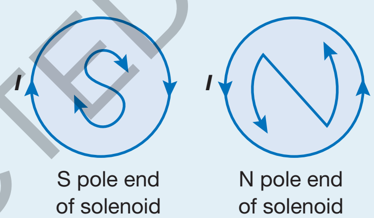
- The direction of the magnetic field produced by a solenoid can be determined using another right-hand grip rule; see figure 5.8. In this case, the right hand grips the solenoid with the fingers pointing in the same direction as the conventional current flowing in the loops of wire and the thumb points to the end of the solenoid that acts like the N pole of a bar magnet; that is, the end of the solenoid from which the magnetic field lines emerge.

FIGURE 5.8 Determining the N pole of a solenoid



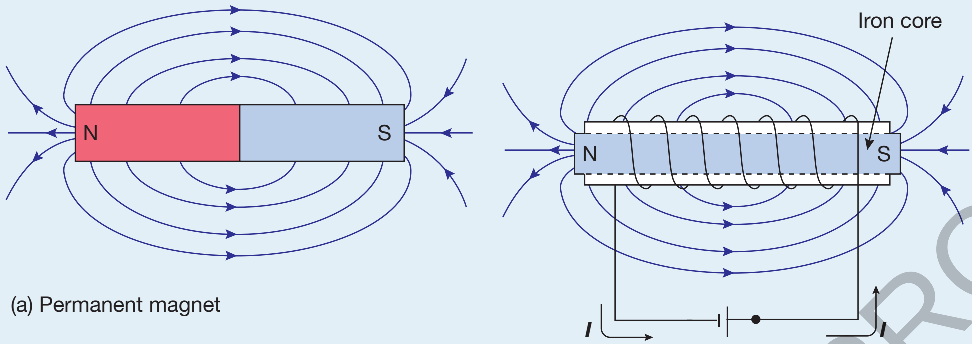
- Another method for determining the poles of a solenoid is to look at a diagram of the ends of the solenoid (see figure 5.9), and mark in the direction of the conventional current around the solenoid. Then mark on the diagram the letter N or S that has the ends of the letter pointing in the same direction as the current. N is for an anticlockwise current, S is for a clockwise current.

FIGURE 5.9 Another method for determining the poles of a solenoid



- An electromagnet is a solenoid that has a soft iron core. When a current flows through the solenoid, the iron core becomes a magnet. The polarity of the iron core is the same as the polarity of the solenoid. The core produces a much stronger magnetic field than is produced by the solenoid alone. In figure 5.10 the magnetic field of a permanent magnet is compared to that of an electromagnet.
- The strength of an electromagnet can be increased by:
  - increasing the current through the solenoid
  - adding more turns of wire per unit length for a long solenoid
  - increasing the amount of soft iron in the core.

FIGURE 5.10 A permanent magnet and an electromagnet. Note the polarity of the iron core.



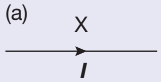
(a) Permanent magnet

(b) Electromagnet

5.2 Exercise 1

Use the right-hand-grip rule to determine the direction of the magnetic field at point X in the following diagrams.

1 (a)



(b)

current into page

2 Six compasses surround a current-carrying wire, as shown. The dark end of the compasses indicates the north pole. Which direction is a current flowing in the wire?

FIGURE 5.11

Working scientifically 5.1

Measuring the strength of a magnetic field

The relationship *FIIB* can be investigated by suspending several loops of wire from a spring balance in a magnetic field and putting a current through the loop. How should the field and the loops be arranged so that the force pulls the loops down and stretches the spring balance?

The loops initially stretch the spring balance, giving a reading of their weight. When there is a current through the loop, the magnetic force stretches the balance further. The extra weight is the magnetic force. If the current and the length of the loops are measured, and the number of loops is determined, the strength of the magnetic field can be calculated. Try this out with a horseshoe magnet.

What would happen if the current is reversed?

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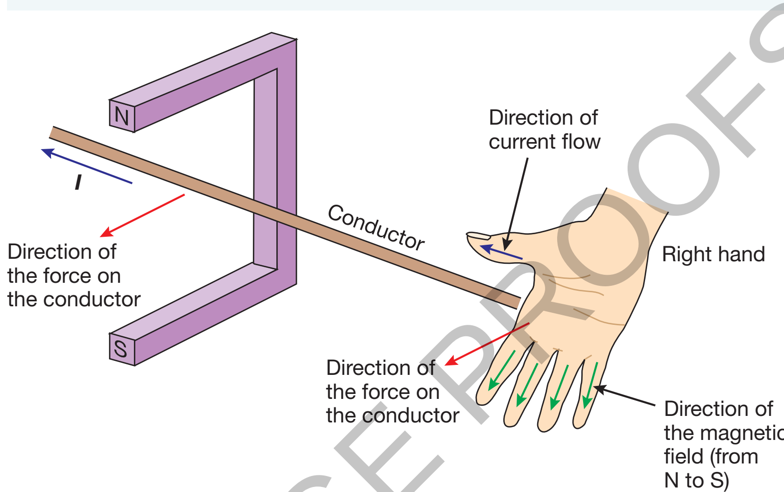
5.3 The motor effect

5.3.1 The right-hand push rule

A current-carrying conductor produces a magnetic field. When the current-carrying conductor passes through an external magnetic field, the magnetic field of the conductor interacts with the external magnetic field and the conductor experiences a force. This effect was discovered in 1821 by Michael Faraday (1791–1867) and is known as the **motor effect**. The motor effect is the action of a force experienced by a current-carrying conductor in an external magnetic field. The direction of the force on the current-carrying conductor in an external magnetic field can be determined using the **right-hand push rule** and can be seen in figure 5.12. The right-hand push rule (also called the right-hand palm rule) is used to find the direction of the force acting on a current-carrying conductor in an external magnetic field.

FIGURE 5.12 The right-hand push rule for a current-carrying conductor



5.3.2 Factors affecting the magnitude of the force

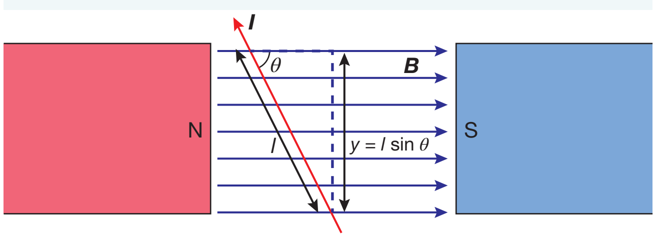
The magnitude of the force on a straight conductor in a magnetic field depends on the following factors:

- the strength of the external magnetic field. The force is proportional to the magnetic field strength, B
- the magnitude of the current in the conductor. The force is proportional to current, I
- the length of the conductor in the field. The force is proportional to the length, l
- the angle between the conductor and the external magnetic field. The force is at a maximum when the conductor is at right angles to the field, and it is zero when the conductor is parallel to the field. The magnitude of the force is proportional to the component of the field that is at right angles to the conductor. If θ is the angle between the field and the conductor, then the force is the maximum value multiplied by the sine of θ.

These factors are shown in figure 5.13 and can be expressed mathematically as:

$F = BIl \sin \theta$.

FIGURE 5.13 A conductor at an angle to a magnetic field



5.3 SAMPLE PROBLEM 1

FORCE ON A CURRENT-CARRYING CONDUCTOR

If a conductor of length 8.0 cm carries a current of 30 mA, calculate the magnitude of the force acting on it when in a magnetic field of strength 0.25 T if:

(a) the conductor is at right angles to the field
(b) the conductor makes an angle of 30° with the field
(c) the conductor is parallel with the field.

SOLUTION:

Use the equation:

$$F = BIl \sin\ \theta$$

where

$$l = 8.0 \times 10^{-2}\ \text{m}$$
$$I = 3.0 \times 10^{-2}\ \text{A}$$
$$B = 0.25\ \text{T.}$$

(a) $F = BIl \sin 90°$

$$= 3.0 \times 10^{-2} \times 8.0 \times 10^{-2} \times 0.25 \times 1$$
$$= 6.0 \times 10^{-4}\ \text{N}$$

(b) $F = BIl \sin 30°$

$$= 3.0 \times 10^{-2} \times 8.0 \times 10^{-2} \times 0.25 \times 0.5$$
$$= 3.0 \times 10^{-4}\ \text{N}$$

(c) $F = BIl \sin 0°$

$$= 3.0 \times 10^{-2} \times 8.0 \times 10^{-2} \times 0.25 \times 0$$
$$= 0$$

5.3 Exercise 1

1 Calculate the force on a 100 m length of wire carrying a current of 250 A when the strength of Earth's magnetic field at right angles to the wire is 5.00×10^{-5} T.

2 The force on a 10 cm wire carrying a current of 15 A when placed in a magnetic field perpendicular to *B* has a maximum value of 3.5 N. What is the strength of the magnetic field?

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5.4 The interaction between two parallel current-carrying wires

5.4.1 Forces between two parallel conductors

If a finite distance separates two parallel current-carrying conductors, then each conductor will experience a force due to the interaction of the magnetic fields that exist around each.

Figure 5.14, shows the situation where two long parallel conductors carry currents $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ in the same direction.

Figure 5.14a shows the magnetic field of conductor 1 in the region of conductor 2. Conductor 2 is cutting through the magnetic field due to conductor 1. The right-hand push rule shows that conductor 2 experiences a force directed towards conductor 1.

Similarly, figure 5.14b shows the magnetic field of conductor 2 in the region of conductor 1. The right-hand push rule shows that conductor 1 experiences a force directed towards conductor 2. This means that the conductors are forced towards each other.

FIGURE 5.14 The forces acting on two long parallel conductors carrying currents in the same direction

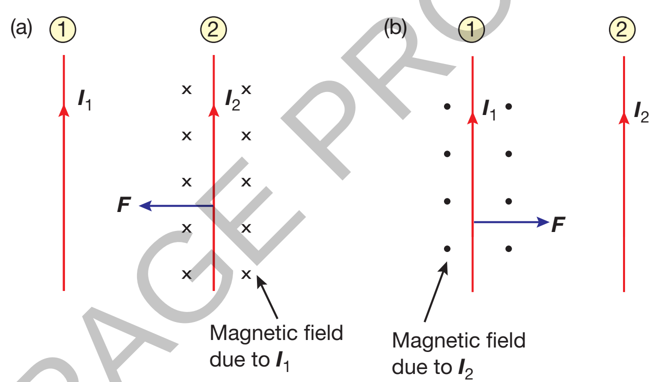


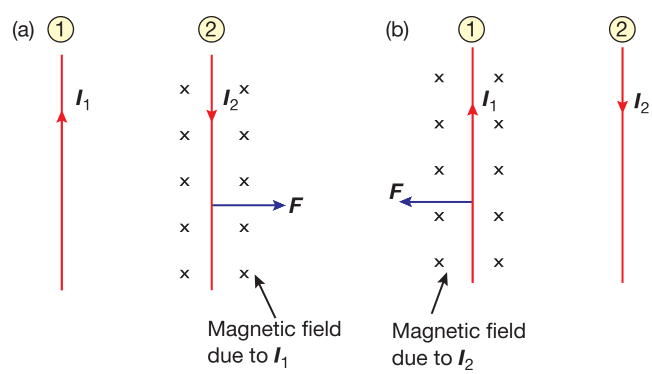
Figure 5.15 shows the situation where two long parallel conductors carry currents $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ in opposite directions.

Figure 5.15a shows the magnetic field of conductor 1 in the region of conductor 2. The right-hand push rule shows that conductor 2 experiences a force directed away from conductor 1.

Similarly, figure 5.15b shows the magnetic field of conductor 2 in the region of conductor 1. The right-hand push rule shows that conductor 1 experiences a force directed away from conductor 2. This means that the conductors are forced apart.

Note that the magnitude of the forces acting on each pair of wires is equal, but the directions are opposite. This is true even if the conductors carry currents of different magnitudes.

FIGURE 5.15 The forces acting on two long parallel conductors carrying currents in opposite directions



5.4.2 Determining the magnitude of the force between two parallel conductors

The magnetic field strength at a distance, d, from a long straight conductor carrying a current, I, can be found using the formula:

$$B = \frac{kI}{d}$$

where

$k = 2.0 \times 10^{-7}\,\text{N A}^{-2}$.

Note that in this equation k is a constant derived from careful experimentation and that d is the perpendicular distance from the wire to the point at which B is to be calculated.

Figure 5.16 shows two parallel conductors, X and Y, that are carrying currents $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ respectively. X and Y are separated by a distance of d.

The magnetic field strength in the region of Y due to the current flowing through X is:

$$B_X = \frac{kI_1}{d}.$$

The magnitude of the force experienced by a length, l, of conductor Y due to the external magnetic field provided by conductor X is:

$$F = I_2 l B_X, \text{ or}$$

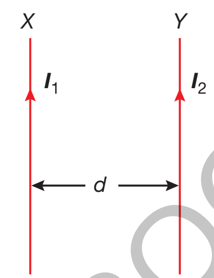
$$F = I_2 l \left(\frac{kI_1}{d}\right)$$

This can be rearranged to give the formula:

$$\frac{F}{l} = k\frac{I_1 I_2}{d}.$$

A similar process can be used to show that the same formula will give the force experienced by a length, l, of conductor X due to the magnetic field created by the current flowing in conductor Y.

FIGURE 5.16 Two parallel current-carrying conductors



5.4 SAMPLE PROBLEM 1

FORCE BETWEEN PARALLEL CONDUCTORS

What is the magnitude and direction of the force acting on a 5.0 cm length of conductor X in figure 6.15 if I_1 is 3.2 A, I_2 is 1.2 A, and the separation of X and Y is 25 cm?

SOLUTION:

Quantity	Value
F	?
k	2.0×10^{-7} N A^{-2}
l	5.0×10^{-2} m
l_1	3.2 A
l_2	1.2 A
d	0.25 m

Use the equation:

$$\frac{F}{l} = \frac{kI_1 I_2}{d}.$$

This transposes to give:

$$F = \frac{k\,l\,I_1 I_2}{d}$$
$$= \frac{2.0 \times 10^{-7} \times 5.0 \times 10^{-2} \times 3.2 \times 1.2}{0.25}$$
$$= 1.5 \times 10^{-7}\text{ N}.$$

To determine the direction of the force, first find the direction of the magnetic field at X, due to the current in Y, by using the right-hand grip rule. The field is out of the page. Next determine the direction of the force on X using the right-hand push rule. This shows that the force is to the right.

5.4.3 Determining the magnitude of the force between two parallel conductors

Determining the value of k

The force between two parallel conductors in free space is often stated

$$\frac{F}{L} = \frac{\mu_o}{2\pi} \times \frac{I_1 I_2}{r}$$

μ_o is the **magnetic permeability** of free space (or a vacuum). The magnetic permeability of a substance is the ability of a material to support the formation of a magnetic field. It is the degree of magnetisation that a material obtains in response to an applied magnetic field.

In general, the permeability of a substance is the ability of that substance to allow something to pass through it. You may have heard of semipermeable membranes in osmosis.

μ_o has a precise value of $4\pi \times 10^{-7}$ N A^{-2}.

The magnetic permeability of air has approximately the same value as the magnetic permeability of free space.

Hence, in air or a vacuum, $\frac{\mu}{4\pi} = 2.0 \times 10^{-7}$ N A^{-2} and the equation can be written as

$$F = \frac{k I_1 I_2 L}{r}$$

Where k = 2.0×10^{-7} N A^{-2}.

The magnetic permeability of iron is 2.5×10^{-1} N A^{-2}. Iron can become much more magnetised than air.

5.5 SI definition for electrical current; the ampere and Newton's Third Law of Motion

5.5.1 The ampere

The ampere is the unit for electrical current in the System International (SI) of Units. The formal definition of the ampere states: One ampere is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in vacuum, would produce between those conductors a force equal to 2×10^{-7} newtons per metre of length.

This is an application of Newton's Third Law of Motion which states: In a two-body system, if body A exerts a force on body B, then body B exerts a force on Body A that is equal in magnitude, but opposite in direction.

Newton's Third Law of Motion is sometimes stated: For every action there is an equal and opposite reaction.

If one wire applies a force to a second wire, the second wire will apply a force that is equal in magnitude and opposite in direction on the first wire.

5.6 Review

5.6.1 Summary

- According to the motor effect, a current-carrying conductor in a magnetic field will experience a force that is perpendicular to the direction of the magnetic field. The direction of the force is determined using the right-hand push rule.
- The right-hand push rule is applied by:
  - extending the fingers in the direction of the magnetic field
  - pointing the thumb in the direction of the current in the conductor.

- The palm of the hand indicates the direction of the force.
- The magnitude of the force, F, on a current-carrying conductor is proportional to the strength of the magnetic field, B, the magnitude of the current, I, the length, L, of the conductor in the external field and the sine of the angle between the conductor and the field: $F = BIL\sin\theta$
- If the conductor is at right angles to the magnetic field, the force has the maximum value.
- If the conductor is parallel to the magnetic field, there is no force.
- Two long parallel current-carrying conductors will exert a force on each other. The magnitude of this force is determined using the following formula:

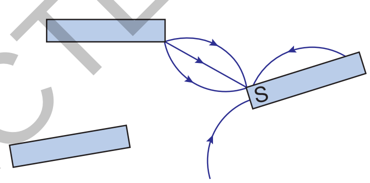
$$\frac{F}{L} = \frac{\mu_o}{2\pi} \times \frac{I_1 I_2}{r}$$

- If the currents in two parallel conductors are running in the same direction, the conductors attract each other. If the currents are in opposite directions, the conductors repel each other.
- One ampere is the constant current which, if maintained in two straight parallel conductors of infinite length and of negligible circular cross-section and placed one metre apart in a vacuum, would produce between those conductors a force equal to 2×10^{-7} newtons per metre of length.

5.6.2 Questions

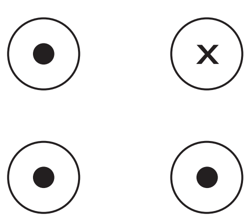
1. State the law of magnetic poles.
2. Draw a bar magnet and the magnetic field around it. Label the diagram to show that you understand the characteristics of magnetic field lines.
3. Are the north magnetic pole of the Earth and the north pole of a bar magnet of the same polarity? Explain your reasoning.
4. Figure 5.17 shows three bar magnets and some of the field lines of the resulting magnetic field.
   (a) Copy and complete the diagram to show the remaining field lines.
   (b) Label the polarities of the magnets.

FIGURE 5.17



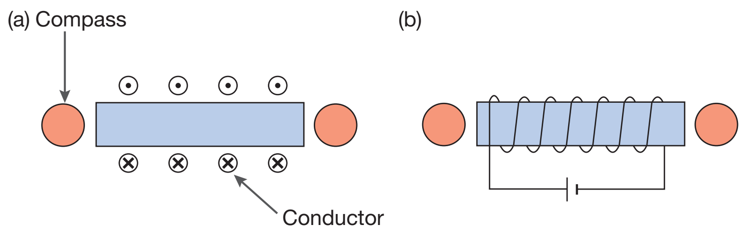
5. Draw a diagram to show the direction of the magnetic field lines around a conductor when the current is (a) travelling towards you and (b) away from you.
6. Each diagram in figure 5.18 represents two parallel current-carrying conductors. In each case, determine whether the conductors attract or repel each other. Explain your reasoning.

FIGURE 5.18



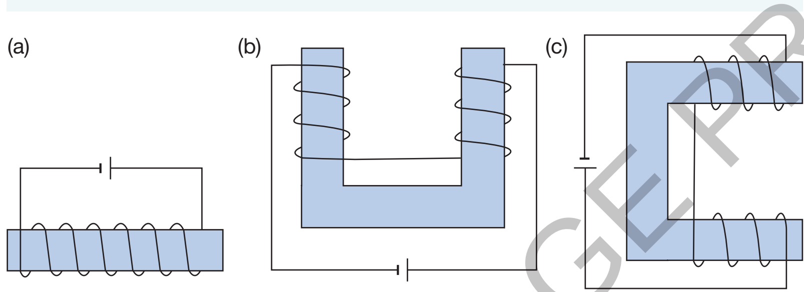
7. Each empty circle in figure 5.19 represents a plotting compass near a coiled conductor. Copy the diagram and label the N and S poles of each coil, and indicate the direction of the needle of each compass.

FIGURE 5.19



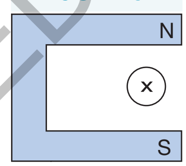
8. The diagrams in figure 5.20 show electromagnets. Identify which poles are N and which are S.

FIGURE 5.20



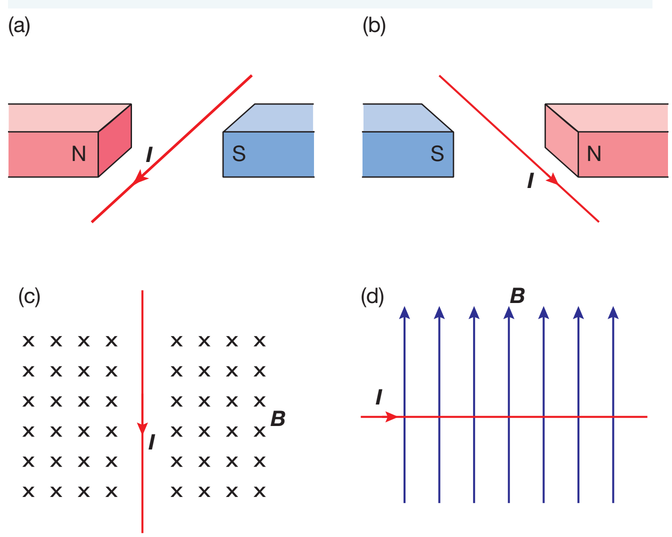
9. In figure 5.21 a current-carrying conductor is in the field of a U-shaped magnet. Identify the direction in which the conductor is forced.

FIGURE 5.21



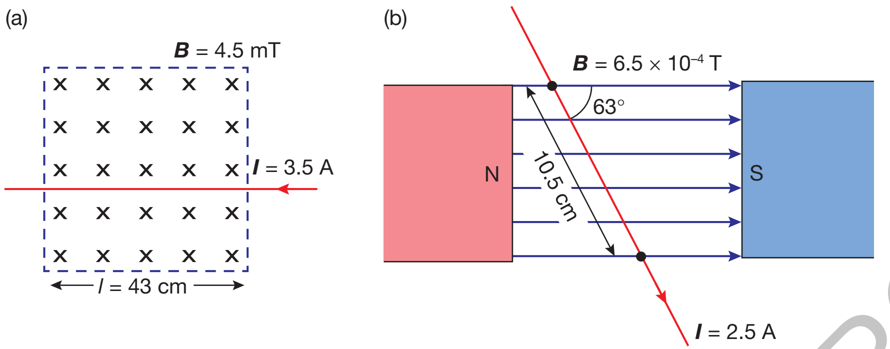
10. Identify the direction of the force acting on each of the current-carrying conductors shown in figure 5.22. Use the terms 'up the page', 'down the page', 'into the page', 'out of the page', 'left' and 'right'.

FIGURE 5.22



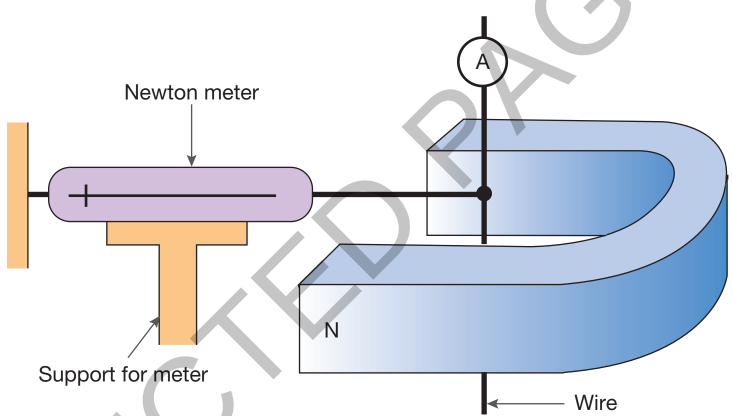
11. Deduce both the magnitude and direction of the forces acting on the lengths of conductors shown in figure 5.23.

FIGURE 5.23



12. A student wishes to demonstrate the strength of a magnetic field in the region between the poles of a horseshoe magnet. He sets up the apparatus shown in figure 5.24.

FIGURE 5.24



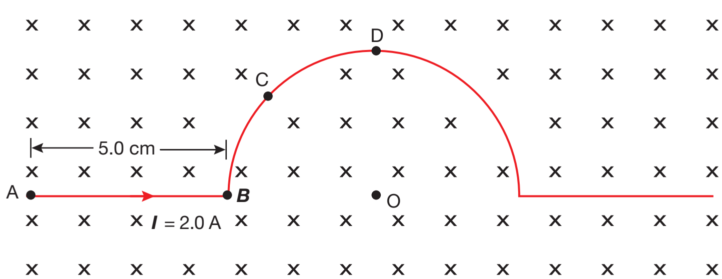
The length of wire in the magnetic field is 2.0 cm. When the ammeter reads 1.0 A, the force measured on the newton meter is 0.25 N.

(a) What is the strength of the magnetic field?

(b) In this experiment the wire moves to the right. In what direction is the current flowing, up or down the page?

13. A wire with the shape shown in figure 5.25 carries a current of 2.0 A. It lies in a uniform magnetic field of strength 0.60 T.

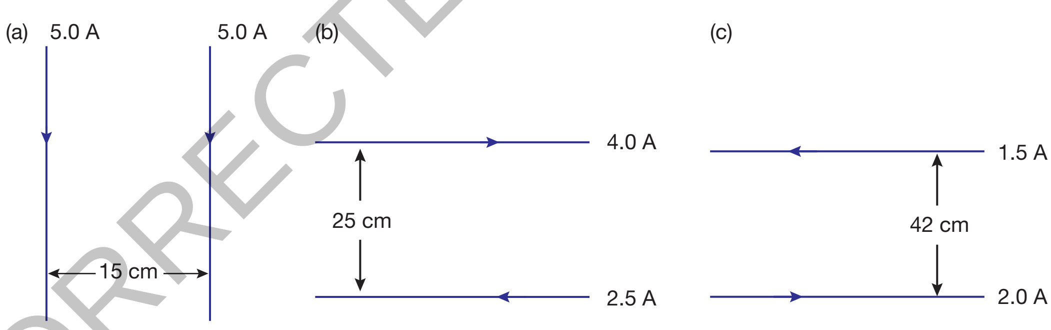
FIGURE 5.25



(a) Calculate the magnitude of the force acting on the section of wire, AB.
(b) Which of the following gives the direction of the force acting on the wire at the point, C?
   i. Into the page
   ii. Out of the page
   iii. In the direction OC
   iv. In the direction CO
   v. In the direction OD
   vi. In the direction DO
(c) Which of the following gives the direction of the net force acting on the semicircular section of wire?
   i. Into the page
   ii. Out of the page
   iii. In the direction OC
   iv. In the direction CO
   v. In the direction OD
   vi. In the direction DO

14. A wire of length 25 cm lies at right angles to a magnetic field of strength 4.0×10^{-2} T. A current of 1.8 A flows in the wire. Calculate the magnitude of the force that acts on the wire.
15. Two long straight parallel current-carrying wires are separated by 6.3 cm. One wire carries a current of 3.4 A upward and the other carries a current of 2.5 A downward.
   (a) Evaluate the magnitude of the force acting on a 45 cm length of one of the wires.
   (b) Is the force between the wires attraction or repulsion?
16. Evaluate the magnitude of the force acting on a 40 cm length of one of the two long wires shown in figures 5.26 (a), (b) and (c).

FIGURE 5.26



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PRACTICAL INVESTIGATIONS

Investigation 5.1: The Motor Effect

Aim

To observe the direction of the force on a current-carrying conductor in an external magnetic field.

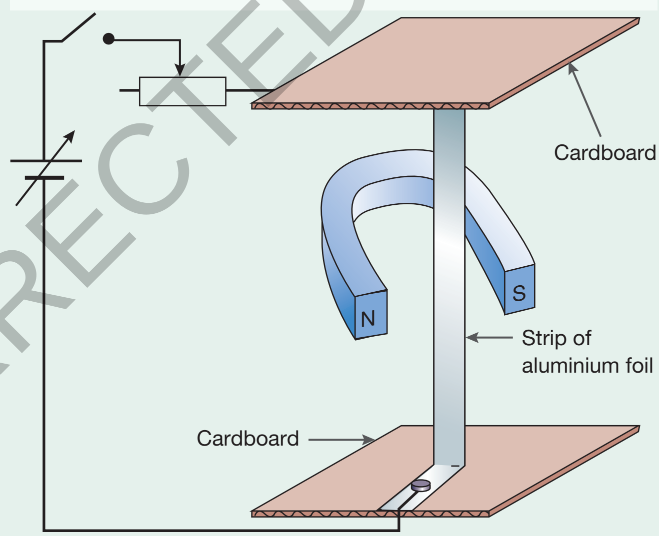
Apparatus

variable DC power supply
variable resistor (15 Ω rheostat)
connecting wires
retort stand
clamp
two pieces of thick card or balsa wood 10 cm × 10 cm
strip of aluminium foil 1 cm × 30 cm (approximately)
two drawing pins
switch
horseshoe magnet

Method

1. Pin the foil strip between the pieces of card. Rest one card on the bench-top and support the other with the clamp and retort stand.
2. Connect the wires to the power pack's DC terminals, switch, variable resistor and strips as shown in figure 5.27. This will produce a current in the strip.
3. Position the horseshoe magnet so that the strip is between the poles. Note the position of the poles of the magnet and the direction of the current through the strip when the switch is closed.
4. Set the power pack to its lowest value and turn it on.
5. Briefly close the switch and record the movement of the foil strip.
6. Turn the magnet over so that the magnetic field is in the opposite direction across the strip.
7. Briefly close the switch and record the movement of the foil strip.

FIGURE 5.27 The set-up for the motor effect activity



Analysis

1. Did the strip experience a force when a current flowed?
2. Verify that the movement of the aluminium strip is in accordance with the right-hand push rule.

Investigation 5.2: The Force Between Two Parallel Current-Carrying Conductors

Aim

To observe the direction of the forces between two parallel current-carrying conductors.

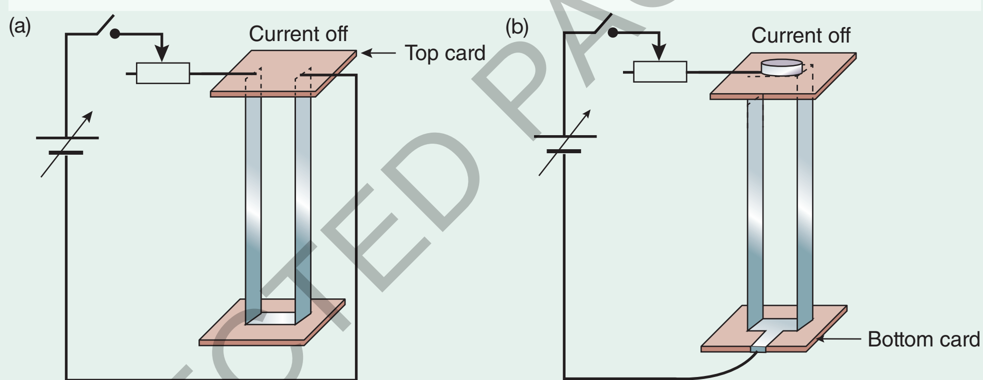
Apparatus

variable DC power supply
variable resistor (15 Ω rheostat)
connecting wires
retort stand
clamp
two pieces of thick card or balsa wood 10 cm × 10 cm
two strips of aluminium foil 1 cm × 30 cm (approximately)
four drawing pins
push switch

Method

1. Pin each foil strip between the pieces of card so that they are parallel when the top card is supported by the clamp and retort stand.
2. Connect the wires to the power pack's DC terminals, switch, variable resistor and strips as shown in figure 5.28a. This will produce currents in the strips that are flowing in opposite directions.
3. Set the power pack to its lowest value and turn it on.
4. Briefly close the switch and record the movement of the foil strips.
5. Connect the wires to the power pack's DC terminals, switch, variable resistor and strips as shown in figure 5.28b. This will produce currents in the strips that are flowing in the same direction.
6. Briefly close the switch and record the movement of the foil strips.

FIGURE 5.28 (a) The set-up for currents flowing in opposite directions (b) The set-up for currents flowing in the same direction



Analysis

Account for your observations.