16.2 Magnets and Motors

SECTION OUTCOMES

- State the motor effect.
- Investigate and communicate factors that affect the force on a current carrying conductor.
- Test a device that operates using the principles of electromagnetism.

KEY TERMS

- motor effect
- right-hand rule #3
- telsa
- torque
- rotor
- armature
- commutator
- split ring commutator

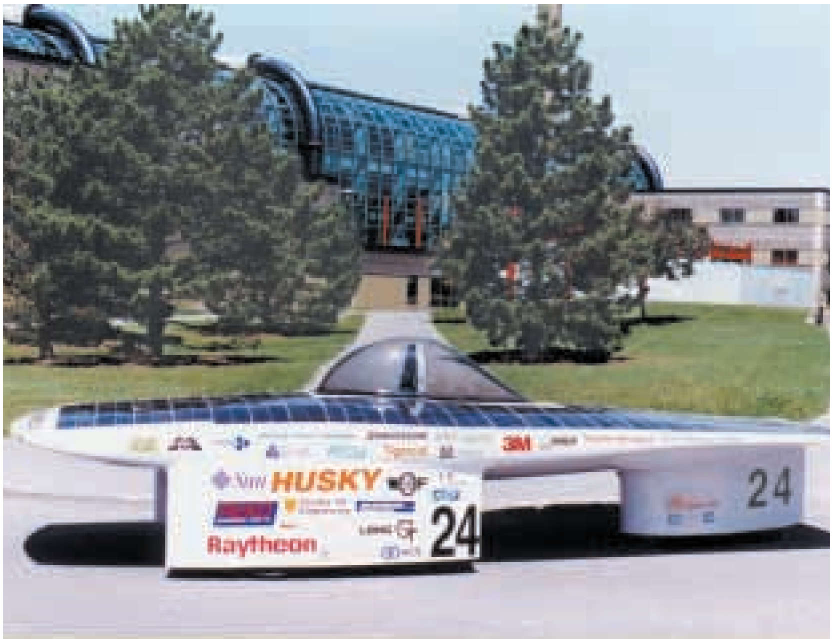

Figure 16.14 Designed to compete, the University of Waterloo's Midnight Sun solar-powered car attends races around the world.

University of Waterloo students are not alone in their effort to further solar-powered vehicle design. Undergraduate students at Queen's University set off in their solar-powered car on July 1, 2000 from Halifax and travelled 6500 km to Vancouver in less than a month. At the time this book was published, this event still held the world record for distance by a solar-powered vehicle. The electric motor was specially designed in a pancake shape to fit inside the low profile of the vehicle. Hybrid cars that use a combination of electric motors and gasoline engines are already gaining popularity.

The study of electric fields and electromagnetism in the previous section of this chapter is just the tip of the electromagnetic iceberg. Converting electrical energy to thermal energy is an easy task; you simply pass the current through a resistance and the resistance heats up. It was Oersted's discovery of electromagnetism that led to the invention of the electric motor. Currently, over half of the electricity generated in North America is used to run electric motors. It's fortunate that today's electric motors are so efficient; they typically operate at efficiencies greater than 80% in transforming electric energy into rotational motion of the motor, compared with a gasoline engine which operates at less than 30% efficiency.

PROBEWARE

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If your school has probeware equipment, visit the Internet site above and follow the links for several laboratory activities on electric motor efficiency.

Electric Currents in Magnetic Fields

The first current meters, now called tangent galvanometers, consisted of a coil of wire with a compass needle at the centre. When the current flowed through the coil, the needle deflected to the east or west depending on the size and direction of the current. Because the tangent galvanometer had to be very carefully oriented, it was not particularly easy or practical to use (see Figure 16.15).

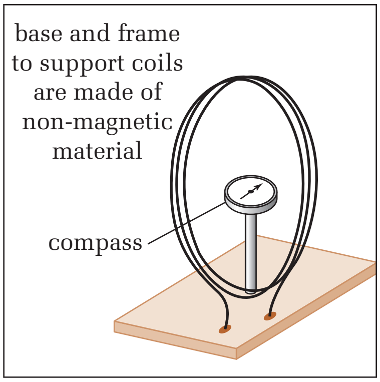


Figure 16.15 The coils of the tangent galvanometer are set so that the plane of the coils is parallel to the direction of the compass needle. When a current is passed through the coils, the compass needle deflects to the left or the right from that plane. The tangent of the angle of deflection is proportional to the size of the current.

According to Newton's third law of motion, for every action there is an equal and opposite reaction. If the current in a conductor caused a magnetic field that exerted a force on a magnet, then the magnet must interact with the magnetic field from the current to exert a force on the conductor. In a tangent galvanometer, if the coil is exerting a force on the magnet at its centre to make it turn clockwise, then the magnet must be exerting a force on the coil trying to make it turn counter-clockwise.

The simplest form of the interaction of a magnet on a current-carrying conductor can be observed when a segment of wire carries a current linearly through a magnetic field. In Figure 16.16, a conductor carries a current upward past the N-pole of a bar magnet. First, let's approach this from the point of view of the conductor.

Using right-hand rule #1, as shown, the current creates a magnetic field consisting of circular field lines around the conductor. The magnetic field of the conductor exerts a magnetic force on the N-pole of the magnet that acts in a direction tangent to the direction of the lines of force where they contact the magnet. (It is important to note that magnets do not react to their own magnetic fields.) Because of the magnetic field of the conductor, the N-pole of the bar magnet experiences a force directly into the page. If the N-pole of the magnet, in Figure 16.16, is free to move, it will move away from the observer into the page.

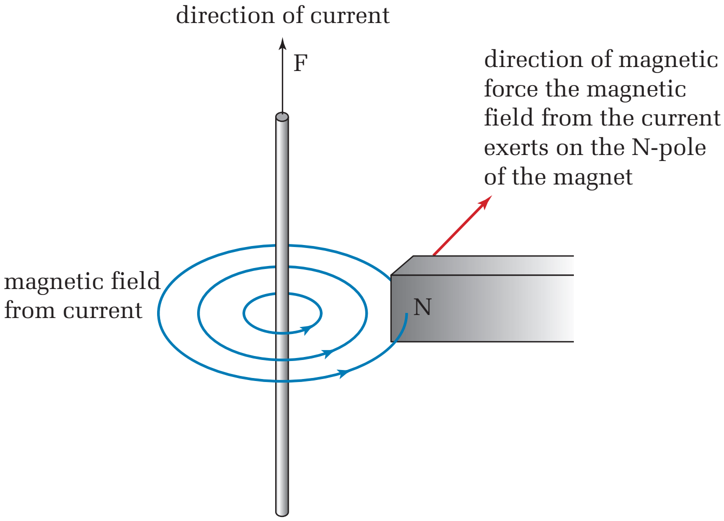


Figure 16.16 At the position of the N-pole of the bar magnet, the field lines from the current's magnetic field point directly into the page; therefore, the N-pole of the magnet experiences a force directly into the page.

From the perspective of the magnet, it sees the conductor carrying a current through its magnetic field. Since the magnetic field from the conductor exerts a force on the magnet, Newton's third law says that the magnet exerts an equal, but oppositely directed, force on the conductor. Right-hand rule #3, describes the direction of the force exerted on the conductor by the magnet's field.

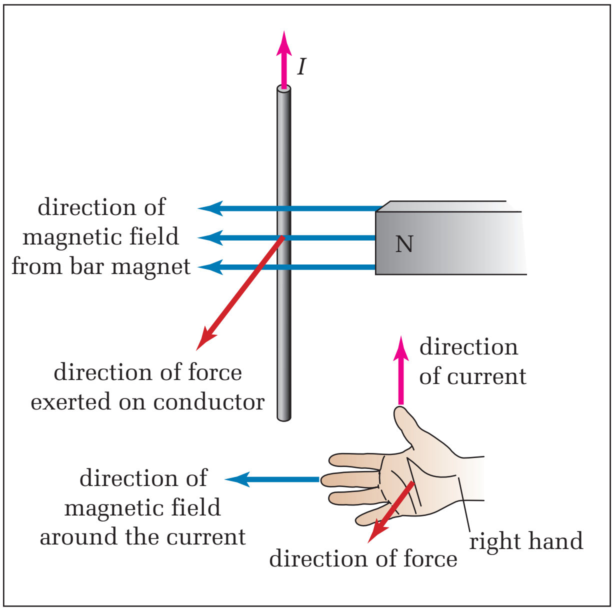
Right-hand Rule #3

Extend your right hand so that the fingers, thumb, and palm form a flat surface with the thumb at right angles to the fingers. Align the thumb along the conductor pointing in the direction of the current and the fingers pointing in the direction of the magnetic field (from the magnet) that is passing the conductor. The palm, then, is facing in the direction of the force that the field from the magnet exerts on the conductor (see Figure 16.17).

The magnetic field of the magnet points away from the N-pole of the magnet past the conductor. If the conductor were an ordinary magnet, its N-pole would experience a force directly away from the magnet (to the right). But the conductor has no N-pole or S-pole. Instead, the magnetic field from the magnet exerts a force at right angles to both the direction of the current and the direction of the magnet's field. Notice that all three directions (the current, the field, and the force) are all at right angles to each other (mutually perpendicular). It's easy to remember how to apply the rule if you think of the thumb, the fingers, and then the palm. There is one current (the thumb) passing through many field lines (the fingers) and (the palm) "pushes" in the direction of the force on the conductor (Figure 16.17). This phenomenon is called the **motor effect** since it is the driving force that makes electric motors run.

At this point, it is important to realize that if the current crosses the field at an oblique angle, rather than at right angles, you must identify the direction of the component of the magnetic field that lies perpendicular to the current in order to apply **right-hand rule #3**. If the direction of the magnetic field is parallel to the current, then there is no component of the field perpendicular to the current, and as a result there is no force exerted by the field on the conductor.

Figure 16.17 A conductor that carries a current at right angles to a magnetic field experiences a force at right angles to both the current and the direction of the field. This direction can be predicted by using right-hand rule #3.



INVESTIGATION 16-C

The Motor Effect

TARGET SKILLS

- **Predicting**
- **Modelling concepts**

When a current passes at right angles through a magnetic field, the current (and thus the conductor that carries it) experiences a force at right angles to both the direction of the current and the field through which it is passing.

Problem

In this investigation, you will determine if that force exists and if the direction of the force is correctly predicted by right-hand rule #3.

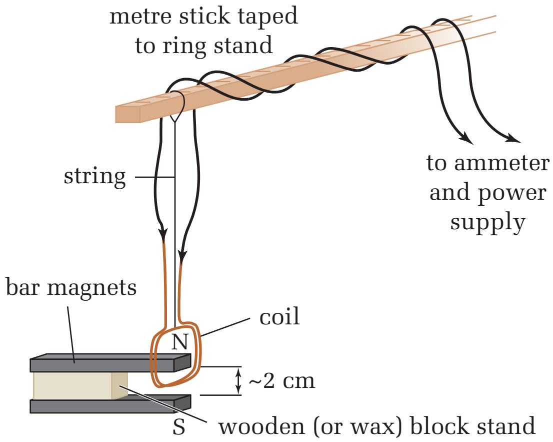
Equipment

- bar magnets (2) or a horseshoe magnet
- wire (about 2 m long to make a coil)
- power supply
- ammeter (0 to 10 A)
- resistor (≈1 Ω, exact value is not important)
- retort stand (2)
- ring clamp
- string
- wax block
- elastic bands

Part 1

Procedure

1. Wrap the 2 m segment of wire around a block that is about 2 cm × 2 cm to make a coil with at least 20 turns. Leave the ends about 10 cm long to connect the coil to the leads from the circuit.
2. Set up the apparatus as shown on the upper right. Suspend the coil so that its bottom edge is between the poles of the two bar magnets (or the horseshoe magnet) as shown.



3. Turn up the potential difference of the power supply very slightly to check that the meter is connected correctly.
4. Once the circuit is connected correctly, increase the potential difference (until a current of about 5 A is reached).
5. As the current is increased, observe the coil for movement.
6. Draw a sketch showing the direction of the current, the magnetic field from the magnet, and the direction of movement.
7. Apply right-hand rule #3 to see if the movement that was observed was in the direction of the predicted force.
8. Reverse the direction of the magnetic field. Repeat steps 4 through 7.
9. Reverse the direction of the current in the coil. Repeat steps 4 through 7.

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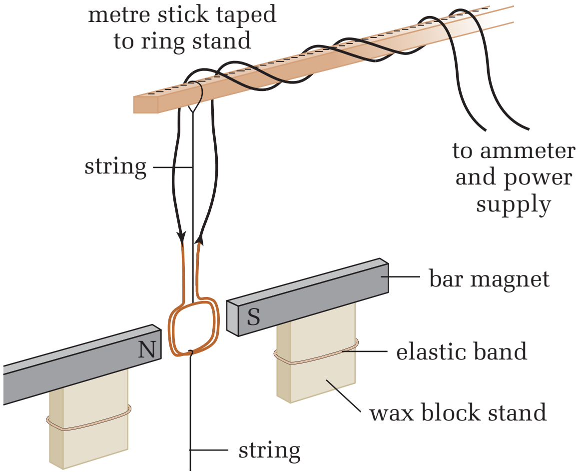
Part 2

Procedure

1. Position the magnets so that both edges of the coil are between the poles of the magnet as shown below. If you attach a string to the bottom of the coil, as shown in the diagram, and hold it gently down, it will stabilize the motion of coil so that the motion caused by the field is easier to observe.



2. Increase the potential difference of the power supply to about 5 A (or to a current that provided observable results during Part 1).
3. Observe the reaction of the coil to the field.
4. Draw an accurate sketch of the motion of the coil with respect to the direction of the field. Make sure you include the directions of the current and the magnetic field, as well as the forces experienced by the coil.
5. Apply right-hand rule #3 to the system to determine if the observed reaction of the coil could be predicted.
6. Reverse the direction of the magnetic field. Repeat steps 2 to 5.
7. Reverse the direction of the current in the coil. Repeat steps 2 to 5.

Analyze and Conclude

1. In Part 1, did right-hand rule #3 correctly predict the movement of the coil when the current was (a) perpendicular, (b) oblique, and (c) parallel to the field?
2. In Part 1, did any unexpected movement of the coil occur? Try to explain these movements, if any.
3. Answer the following questions about Part 2:
   (a) Explain why the coil moves as it does? Why does it stop moving where it does?
   (b) Does right-hand rule #3 correctly predict the motion of the coil?
   (c) Apply right-hand rule #3 to the top and bottom edges of the coil. Does the rule predict that these edges experience a force? Explain why the coil does not seem to respond to the forces on the top and bottom edges of the coil.

Apply and Extend

4. Could the coil be made to move away from the position it took up when the current was first turned on? Explain how this could happen.

UNIT PROJECT PREP

Motors rely on the interaction between electricity and magnetism.

- How important is magnetic field strength to motor design?
- How does the shape of the conductor in the magnetic field affect its operation?

Defining the Ampere

On September 4, 1820, Ampère read an account of Oersted's discovery of electromagnetism. On November 6th, he published his paper on electromagnetism which has become the basis for modern electromagnetic theory. In the paper, Ampère developed his famous mathematical law that describes the relationship between the current in a conductor and the magnetic field that results from it. In the paper Ampère also defined the unit of current, later named in his honour, and created the first "right-hand rule."

Ampère reasoned that if a current-carrying conductor created a magnetic field about itself, then two current-carrying conductors should interact by attracting or repelling each other in the same way as two magnets. To test this theory, he placed two conductors parallel and at a small distance from each other. He discovered that when the currents were in the same direction, the conductors attracted each other, and when currents were in the opposite direction, the conductors repelled each other.

Figure 16.18 shows two parallel conductors, A and B, carrying currents in the same direction. The lines of force (in blue) represent the magnetic field from conductor A. Right-hand rule #1 can be used to verify that, at the position of conductor B, these lines point vertically upward. Right-hand rule #3 can be used to verify that the direction of the magnetic force on the current in conductor B is toward conductor A.

PHYSICS FILE

André Marie Ampère (1775-1836) was known mainly for his genius in mathematics. He began to read books on mathematics at the age of 13, and by age 16, he was writing papers on various aspects of his studies. In 1804, even though he had never attended a university or earned a degree, he was invited to become a professor of mathematics at the École Polytechnique in Paris. Even though the majority of Ampère's work was in mathematics, the two months he spent on electromagnetism laid the groundwork for the application of mathematics to electromagnetism.

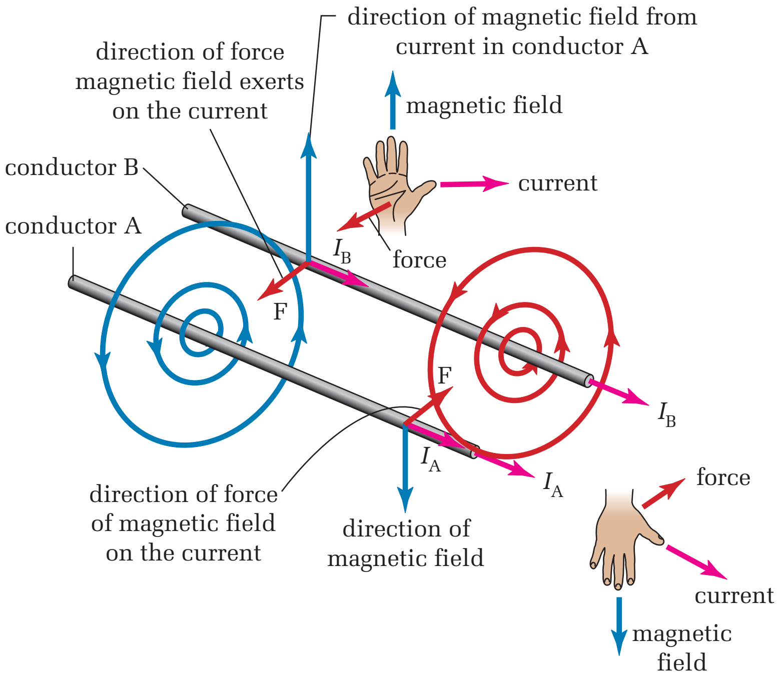
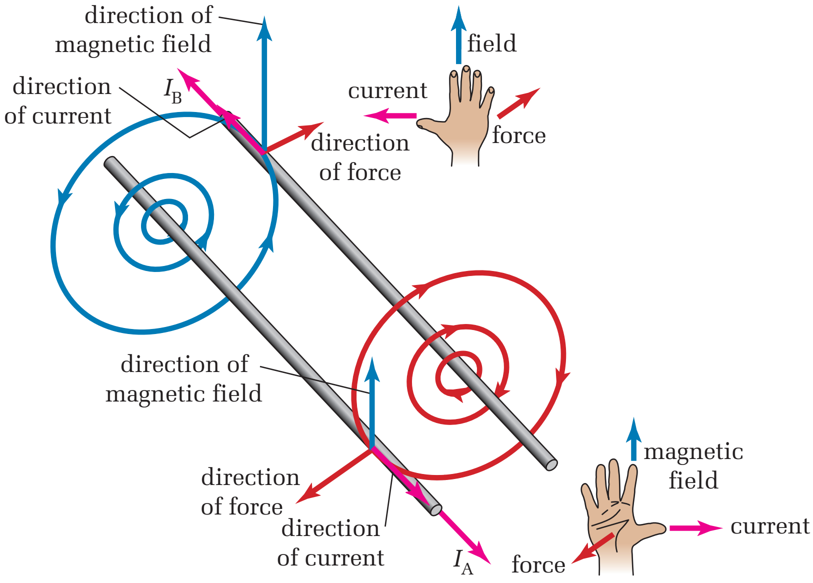


Figure 16.18 Parallel conductors carrying currents in the same direction experience a mutual force of attraction.

Figure 16.19 When parallel conductors carry currents in opposite directions, the magnetic forces cause the conductors to repel each other.



Similarly, the lines of force (in red) represent the magnetic field from the current in conductor B at the position of conductor A. As they pass conductor A, these lines of force point vertically downward. Right-hand rule #3 indicates that the magnetic force on the current in conductor A is toward conductor B. Therefore, the two conductors appear to be attracted to each other.

Figure 16.19 shows two parallel conductors, A and B, carrying currents in opposite directions. Applying right-hand rule #3, in the same way as shown in Figure 16.18, will reveal why these two conductors repel each other.

Ampère discovered that the force (F) between the current-carrying conductors varied directly as the current in conductor A ($F \propto I_A$), directly as the current in conductor B ($F \propto I_B$), directly as the length ($F \propto L$) of the parallel conductors, and inversely as the distance ($F \propto \frac{1}{d}$) between the conductors. These relationships can be written, as shown, in one relationship.

$$F \propto \frac{I_A I_B L}{d}$$

Multiplying the right side by a proportionality constant (K) produces the equation:

$$F = K\frac{I_A I_B L}{d}$$

The units for force (F), length (L) and distance (d) had been defined prior to Ampère's investigation. The unit for current had not been defined so Ampère could now choose a unit for electric current that would produce a proportionality constant of any desired value. For example, the unit of force (1 N) was chosen to be the force that would cause one unit of mass (1 kg) to accelerate at one unit of acceleration (1 m/s^2). Similarly, the unit of resistance (1Ω) was chosen so that one unit of potential difference (1 V) would cause one unit of current (1 A) to move through it.

Ampère did something that was unique in science. He chose the unit of current to be the current that, when flowing in each conductor, would cause the force of attraction or repulsion between the conductors to be exactly 2×10^{-7} newtons per metre of conductor. Because of this choice, the value of the proportionality constant is, by defintion, exactly 2×10^{-7} N/A^2. Had he chosen the current large enough to make $K = 1$, you would probably be more familiar with currents of milliamperes (mA) or microamperes (μA) rather than amperes (A).

One point that is often confusing to students of physics is the relationship between the unit of current and the unit of charge. Usually, current is defined in terms of the movement of a particular quantity per unit time. Water currents, for example, are often measured in litres per second. Therefore, it is often assumed that the unit of current (A) is defined in terms of the quantity of charge that moves per unit time, coulombs per second (C/s). But that is not the case; in fact the reverse is true. The unit of charge (one coulomb) is by definition the amount of charge that is moved by a current of one ampere in one second (1 C = 1 A·s).

PHYSICS FILE

Had Ampère decided that one unit of current (1 A) in two conductors of one unit length (1 m) separated by one unit of distance (1 m) would cause one unit of force (1 N) then the value of the proportionality constant would have been, by definition equal to one. But the force of interaction between two current-carrying conductors is very weak. To produce a force of one newton would have required a current much greater than Ampère's batteries could have produced.

The Motor Force: Quantitative Analysis

When a conductor carries a current through a magnetic field, several factors affect the size of the force exerted on the conductor. First, magnitude of the force (F) exerted varies directly as the magnitude of the magnetic field ($B_\perp$) that acts perpendicular to the conductor. Second, the magnitude of the force varies directly as the magnitude of the current (I). Third, the magnitude of the force varies directly as the length of the conductor inside the field (L). Mathematically, the above statements can be written as

$$\begin{aligned} F &\propto B_\perp \\ F &\propto I \\ F &\propto L \end{aligned}$$

Combined mathematically, they become

$$\begin{aligned} F &\propto ILB_\perp \\ F &= kILB_\perp \end{aligned}$$

where k is the proportionality constant.

When this relationship was first discovered, the units for all the quantities except magnetic field intensity (B) had been defined. Thus, it was possible to define the **tesla**, the unit of magnetic field intensity in terms of the force exerted on a current in the conductor. In this way, the value of k could be made equal to one (1). Rearranging in terms of the other variables, the magnetic field intensity is:

$$B_{\perp} = \frac{F}{IL}$$

This equation shows the relationship between the magnitudes of the variables involved. To find the directions, you must apply right-hand rule #3. Notice that the equation only works for magnetic fields that are perpendicular to the current. As you might expect, the force is proportional to the component of the field that is perpendicular to the direction of current flow.

If a coil with n (n) turns of wire passes through a field, then the length of conductor inside the field is found by taking the product of number of turns in the coil (n) and the length of an individual turn (ℓ). Therefore

$$L = n\ell$$

MAGNETIC FIELD INTENSITY AND MOTOR FORCE

The magnetic field intensity perpendicular to the conductor is the quotient of the motor force, the current, and length of the conductor that is in the field.

$$B_{\perp} = \frac{F}{IL}$$

$$L = n\ell$$

Quantity	**Symbol**	**SI unit**
magnetic field intensity	B	T (tesla)
"perpendicular to"	$\perp$	
motor force	F	N (newton)
current	I	A (amp)
length of conductor	L	m (metre)
number of coil turns	n	no unit
length of each turn	ℓ	m (metre)

Unit Analysis

By definition in the first formula, 1 tesla $= \dfrac{(1\text{ newton})}{(1\text{ amp})(1\text{ metre})}$

$$\mathrm{T} = \frac{\mathrm{N}}{\mathrm{A}\cdot\mathrm{m}}$$

MODEL PROBLEM

Calculating Magnetic Field Strength

A length of straight conductor carries a current of 4.8 A into the page at right angles to a magnetic field. The length of the conductor that lies inside the magnetic field is 25 cm (0.25 m). If this conductor experiences a force of 0.60 N to the right, what is the magnetic field intensity?

Frame the Problem

- Since it is known that the current is at right angles to the field, the formula for magnetic field strength applies to this problem.
- Right-hand rule #3 can be used to find the direction of the field.

Identify the Goal

Find the magnetic field intensity acting on the current.

Variables

Known	Unknown
$F = 0.60\ \text{N}$	$B_\perp$
$I = 4.8\ \text{A}$	
$L = 0.25\ \text{m}$	

Strategy

Calculations

Strategy	Calculations
State the equation relating magnetic field strength to force, current, and conductor length.	$B_\perp = \dfrac{F}{IL}$
Substitute the known values into the equation.	$B_\perp = \dfrac{0.60\ \text{N}}{(4.8\ \text{A})(0.25\ \text{m})}$
A $\dfrac{\text{N}}{\text{A m}}$ is equivalent to a T.	$B_\perp = 0.50\ \text{T}$
Apply right-hand rule #3 to find the direction of the magnetic field.	Hold up your right hand with your thumb pointing into the page (away from you). The palm of your hand must face the right hand side of the page (the direction of the force). Then your fingers are pointing in the direction of the field.

The magnetic field strength is 0.50 T toward the top of the page.

PROBLEM TIPS

- Make sure you know that the *current* and the *magnetic field* act at right angles. This information may be given in many different ways in the problem statement so read very carefully.
- Convert the law from the standard form into the form required to solve the problem.
- It is always necessary to solve the direction portion of the problem separately from the calculation, using right-hand rule #3. You must always identify the directions for two of the three vectors (current, field, and force) to find the direction for the third.

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PRACTICE PROBLEMS

1. A magnetic field has an intensity of 1.2 T into the page. A current of 7.5 A flows vertically upward through a conductor that has 0.080 m inside the field. Find the force that the field exerts on the conductor.
2. A coil that consists of 250 turns of wire has an edge 12 cm long that carries a current of 1.6 A to the right. If the edge of the coil is inside a magnetic field of 0.16 T pointing out of the page, what is the force the field exerts on the coil?
3. A coil, consisting of 500 (5.00×10^2) turns of wire has an edge that is 3.60 cm long that passes at a perpendicular angle through a magnetic field of 0.0940 T into the page. If the magnetic force on the edge of the coil is 10.8 N to the right, what was the current through the coil?
4. What magnetic field will exert a force of 22.0 N downward on a coil of 450 turns carrying a current of 3.20 A to the right through the field? The edge of the coil inside the field is 7.50 cm long.

Torque on a Coil

In Part Two of Investigation 16-C, you observed the effect on a coil when two edges were inside the magnetic field. The result was that the coil twisted in the field. The currents in the edges of the coil experience forces in the opposite direction. (right-hand rule #3) These forces create a **torque** (just like a magnetic dipole) about the axis of the coil. If the coil is free to move, the torque will reorient the coil so that its plane is perpendicular to the field. Once the plane of the coil is perpendicular to the field, the forces on the edges of the coil are linearly opposed so that the net force on the coil is zero.

Notice that the coil is now oriented so that the magnetic field due to the current through the coil (use right-hand rule #2) is in exactly the same direction as the field from the magnets. Placing an iron core inside the coil greatly increases the strength of the magnetic field from the current, and thus greatly increases the torque on the coil.

The DC Electric Motor

You now have all the theory needed to design an electric motor. The motor has a coil with an iron core, called the **rotor** or **armature**, surrounded by field magnets. In many motors, the field magnets are electromagnets.

There are two obvious difficulties in electric motor design. First, when the coil turns so the magnetic forces on the edges of the coil are aligned directly opposite each other, it will no longer experience any torque. If you could now reverse the direction of the current, and thus the direction of forces, they would point inward,

ELECTRONIC LEARNING PARTNER

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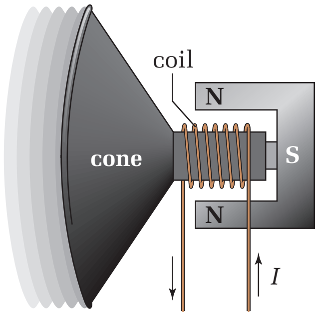
rather than outward, and the edges of the coil would again experience a torque. Second, if the coil keeps turning, the leads to the coil will eventually become so twisted they will break.

The solution to both of these problems was solved by one device called a **split ring commutator**. The split ring commutator, as its name implies, is a brass or copper ring cut into two halves. The **commutator** is attached to the axle of the armature so that it rotates with the coil. One end of the coil is connected to each half of the commutator. Brushes (either metal or carbon) slide on the commutator to pass current from the battery to the coil. At this point, the coil can turn freely without twisting the leads to the coil. Even though a direct current comes from the battery, as the armature rotates, the brushes pass from one segment of the commutator to the other. When the brushes change contact from one half of the commutator to the other, the direction of the current in the coil is reversed. If this occurs at the instant when the coil has reached the point where its plane is perpendicular to the field, the forces on the edge of the coil will reverse and continue to cause the coil to continue its rotation through the field (see Figure 16.20).

PHYSICS FILE



When a current flows through the coil of the loudspeaker, the magnetic field from the coil interacts with the field from the field magnet surrounding the coil. The current that the amplifier sends to the coil varies in strength so that the coil experiences a varying force, pushing it back and forward along its axis. Thus, the cone of the speaker moves back and forth in the same pattern as the fluctuations in the current, setting up a pressure wave that you hear as sound.

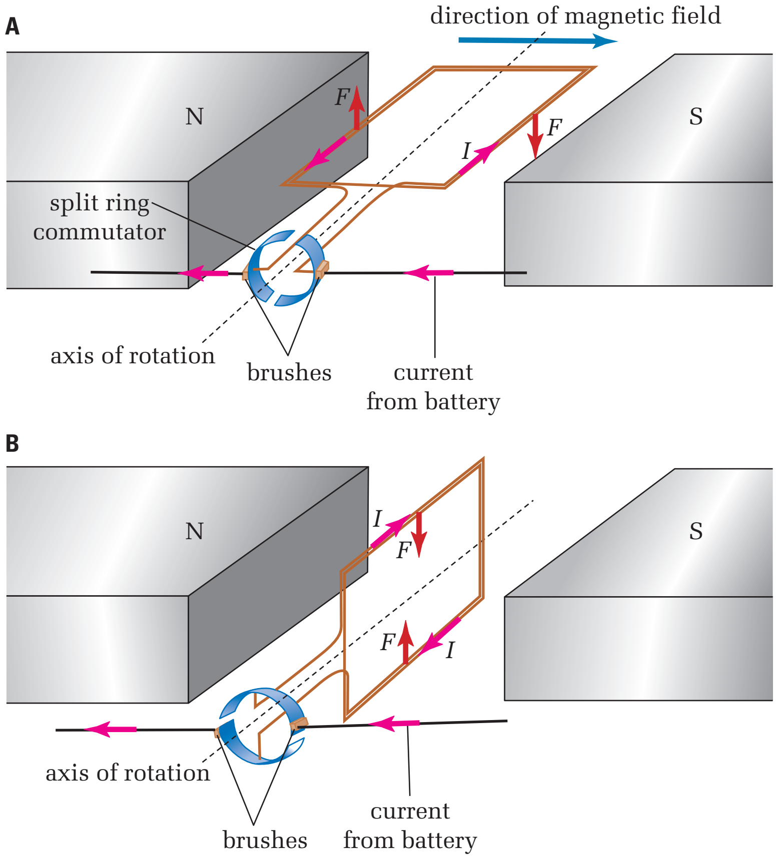


Figure 16.20 **(A)** When the plane of the coil is parallel to the magnetic field, the torque on the coil is at a maximum. **(B)** When the plane of the coil is perpendicular to the field, the torque is at a minimum. At that point, the brushes cross over to the other segment of the commutator, reversing the current in and the forces on the edges of the coil.

CANADIANS IN PHYSICS

Dr. Zahra Moussavi

Due to revolution and war, universities in Iran were closed in 1978. As a result, it took Zahra Moussavi nine years to complete a four-year BSc in electronic engineering. In 1989, Zahra and her family moved to Canada. She obtained an MSc from the University of Calgary and a PhD from the University of Manitoba.

Today, Dr. Moussavi teaches biomedical engineering and does research at the University of Manitoba. With the help of George, she studies the movement of arms and shoulders. Her research will help physicians decide how well a surgery has worked and the nature of the post-surgical rehabilitation that may be required.

Many patients, as the result of a stroke or brain tumour, have difficulty swallowing. Current techniques for detecting abnormalities are inadequate.

Dr. Moussavi is exploring the use of accelerometers as a method of detecting the sounds of swallowing and breathing. This technique has already proven valuable in the analysis of injuries to joints such as knees.

16.2 Section Review

1. C Two materials, A and B, both exhibit strong magnetic attraction when they are brought near a magnet. When the magnet is removed, material A loses its magnetism but material B retains its magnetism. Using domains, explain what happens with the two materials.

2. K/U A magnetic field points directly into the page. A square coil is inside the field so that the plane of the coil is parallel to the surface of the page. From your perspective, looking at the page, the current moves counter-clockwise around the coil. Find the direction of the force on each edge of the coil.

3. K/U A square coil lies in the plane of the page. The current flows in a clockwise direction inside the coil. If the magnetic field is to the right, identify the direction of the force on each edge of the coil.

4. K/U A square coil lies so that its plane is horizontal; two of its edges are parallel to the page and two of its edges are perpendicular to the page. If the magnetic field surrounding the coil points out of the page, in which direction will the coil experience a torque if the current is flowing into the page through the left-hand edge of the coil?

UNIT PROJECT PREP

To improve your motor design, think about the fundamental principles of magnets and motors.

- What is the motor effect?
- Why do current-carrying conductors react to magnetic fields?