16.3 Electromagnetic Induction and Generators

Figure 16.21 Microphones use sound to induce an electric signal.

Microphones are just one of the thousands of devices that convert mechanical energy to electrical energy. In the most common type of microphone, sound waves striking the diaphragm of the microphone cause a tiny coil to move inside a magnetic field. This movement induces the currents that are sent to the amplifier.

Currents from Magnetic Fields

In 1820, Ampère had shown that an electric current produces a steady magnetic field. In 1831, Faraday read of Ampère's findings and, by the principle of symmetry, predicted that a steady magnetic field should produce an electric current. The first few attempts to verify his hypothesis produced no results. On his sixth attempt, his investigations produced a rather surprising result.

On one side of an iron ring, he wound a wire solenoid that he connected to a battery and a switch. On the other side, he wound a wire solenoid that he connected to a galvanometer (Figure 16.22). Faraday thought that when he closed the switch, the current through the first solenoid would create a set of magnetic field lines that would permeate the iron ring. These magnetic field lines flowing through the second solenoid would cause a current that could be detected by the galvanometer.

When Faraday closed the switch, the needle on the galvanometer deflected to show a current, and then, unexpectedly, quickly dropped back to zero. As long as the switch was closed, the current remained at zero. Faraday could easily demonstrate that as long as the switch was closed, there was a magnetic field inside the ring. However, there was no accompanying current in the second solenoid. When he opened the switch, the needle on the galvanometer was again

SECTION OUTCOMES

- Analyze and describe electromagnetic induction in quantitative terms.
- Analyze and predict the behaviour of induced currents using the right-hand rules.
- Hypothesize and test qualitative effects of electromagnetic induction.
- Explain the factors that affect the force on a current carrying conductor in a magnetic field.
- Define and describe Lenz's law.
- Identify the direction of induced electric current resulting from a changing magnetic field.

KEY TERMS

- generator effect
- electromagnetic induction
- AC generator
- slip-ring commutator
- DC generator
- rectified DC current
- alternator
- Lenz's law
- back *emf*
- magnetic damping
- eddy currents

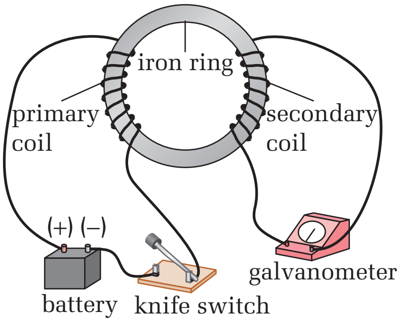


Figure 16.22 Faraday used an iron ring wound with two solenoids to test whether the magnetic field from one solenoid could induce a current in the second solenoid.

momentarily deflected, but in the opposite direction, indicating that for a brief time a current flowed in the opposite direction.

Faraday realized that a *steady* magnetic field through the ring would not generate the desired induced current. The brief pulses of current in the second solenoid, he hypothesized, must have been the result of the fluctuation in the intensity of the magnetic field that occurred when the current was turned on or off.

Once again, the power of Faraday's field theory becomes evident. Faraday reasoned that when he turned the current on, the magnetic field inside the ring grew in intensity. As the magnetic field grew, its field lines expanded outward to fill space around the ring. As the field lines expanded outward, they moved over the coils of the second solenoid. He argued that it was the changing of the field lines across the coils that induced the current in the second solenoid.

Once the current was established in the first solenoid, the size of the magnetic field around the ring became constant. Since the field lines were no longer changing, no current was induced in the second solenoid. However, when the current was turned off, the magnetic field collapsed. The field lines now moved inward across the coils of the second solenoid, causing a brief current in the opposite direction.

To test his hypothesis, Faraday tried moving a magnetic field (from a bar magnet) into and out of a coil of wire. Just as he predicted, the movement of the magnetic field in the vicinity of the coil induced a current in the coil, as long as the magnet was moving. When the motion of the magnet stopped, so did the current. The direction of the induced current was dependent on the *relative motion* of the coil with respect to the magnet (Figure 16.23). Faraday had discovered the **generator effect**: the motion of magnetic field lines past a conductor induces a current in the conductor. The process of generating an electric current in this way is now known as **electromagnetic induction**.

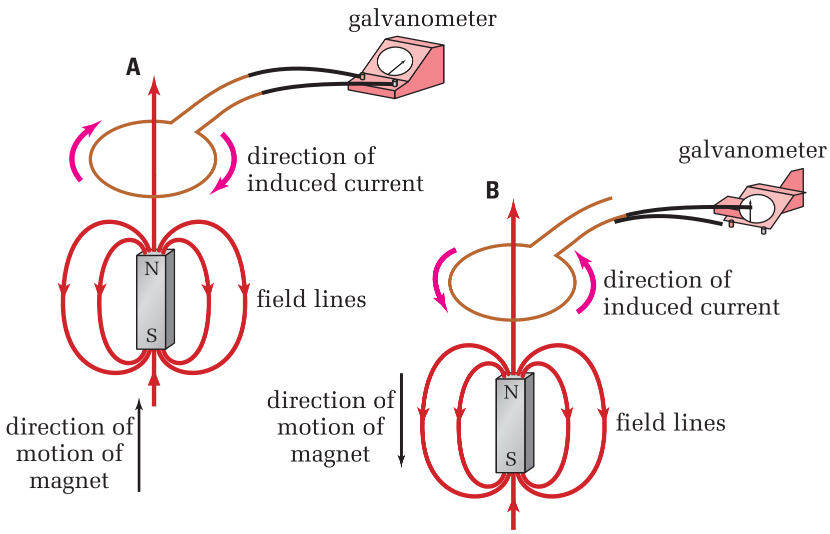


Figure 16.23 The motion of magnetic field lines past a conductor can induce a current in the conductor. The direction of the current depends on the relative motion of the coil with respect to the field lines.

INVESTIGATION 16-D

Faraday's Discovery

TARGET SKILLS
- Analyzing and interpreting
- Performing and recording

When Oersted discovered that an electric current produced magnetic effects, Faraday hypothesized that the reverse might also be true. To test his theory, he constructed a device similar to the one shown in the diagram. Faraday reasoned that when the battery caused the iron bar to become an electromagnet, the magnetic field would induce a current that would be detected by the galvanometer. In this investigation you will discover if Faraday was correct.

Problem

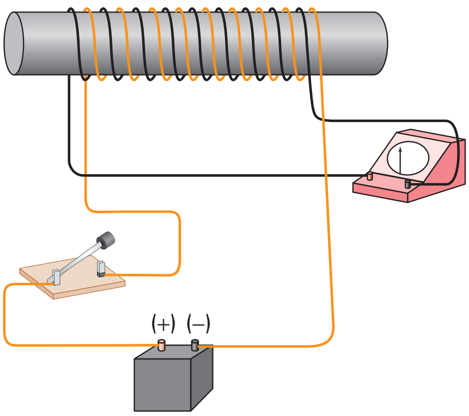
Under what circumstances does a magnetic field induce an electric current?

Hypothesis

When the switch is closed in the apparatus shown below, how do you expect the galvanometer to react, and why?

Equipment

- iron rod (about 10 cm long)
- two 2 m lengths of insulated copper wire
- 6.0 V lantern battery
- switch
- galvanometer
- five alligator clip leads
- masking tape



Procedure

1. Wind the iron rod with at least 50 turns of wire. Leave lengths of wire at each end of the coil to make connections. Wind a second coil of at least 50 turns of wire over the top of the first coil as shown in the diagram. A little masking tape can be used to make sure the coils do not unwind. Connect one coil to a battery with a switch, *keeping the switch open*. Connect the other coil to a galvanometer.

CAUTION The circuit to which the battery is connected is a short circuit. Leave the switch closed only long enough to confirm your observations in the next steps. Avoid touching connections while the switch is closed.

2. Close the switch for a second or two to complete the circuit of the coil connected to the battery. Does a current flow through the galvanometer when there is a current in the coil connected to the battery? If so, how long does the current last? Close and open the switch a few times to verify your observations.

Analyze and Conclude

1. When a current is flowing in the coil connected to the battery, is there a current in the coil connected to the galvanometer?
2. Did the galvanometer react at any time to the current in the coil connected to the battery? If so, when and how?
3. Is the *direction* of the current in the galvanometer affected by the current in the coil connected to the battery?
4. Adjust the connection of the coil connected to the battery so that the current in the coil is reversed. Does this affect the reaction of the galvanometer? If so, describe the effect.
5. What conclusion can you make regarding a magnetic field's ability to induce an electric current in the coil connected to the galvanometer?

INVESTIGATION 16-E

Induced Currents

TARGET SKILLS
- Identifying variables
- Performing and recording
- Communicating results

When a conductor is moved inside a magnetic field, an electric current is induced in the conductor. It would seem natural to assume that the properties of the motion (speed, direction, and orientation) would affect the size and direction of the current. Other possible factors that might affect the induced current are the strength of the field and the length of the conductor inside the field.

In this investigation, you will try to determine, qualitatively, the relationship between the induced current in the coil and the factors that might affect that current.

Problem

Determine a qualitative relationship between the induced current and (a) the motion of the coil, (b) the strength of the magnetic field, and (c) the length of the conductor.

Prediction

For each part of the investigation, make a prediction and record it in your logbook.

Part 1

Predict how the speed of the coil (a) perpendicular to the field and (b) parallel to the field will affect the reading on the galvanometer.

Part 2

Predict the effect of the strength of the magnetic field on the reading of the galvanometer.

Part 3

Predict the effect of the length of the conductor that moves in the field on the reading on the galvanometer.

Equipment

- bar magnets (6)
- wax blocks
- elastic bands
- copper coil (5 turns, 2 cm × 2 cm square)
- copper coil (10 turns, 2 cm × 2 cm square)
- copper coil (20 turns, 2 cm × 2 cm square)
- alligator clip leads
- galvanometer

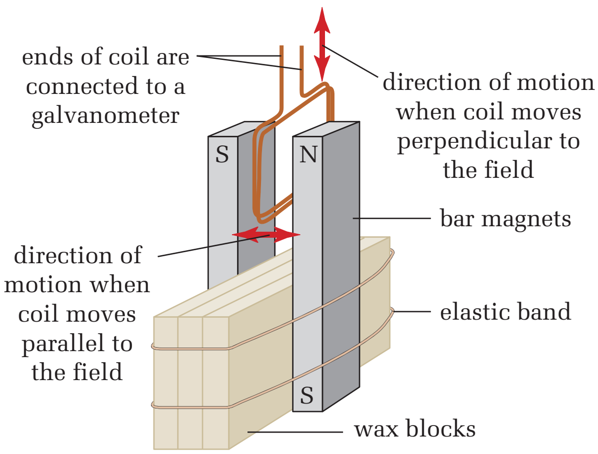
Procedure

Note: It is important that you make careful observations as you proceed through each part of this investigation. The observations you make in Part 1 will affect what you do in Part 2.

Part 1

1. Set up the magnets on the wax blocks with one pair of magnets mounted on them so that the N-pole of one magnet is about three centimetres from and facing the S-pole of the other magnet.

2. Using the coil with 20 turns, move the coil so that one edge of the coil moves across the magnetic field at right angles to the field between the magnets (see below).



3. Observe the motion of the galvanometer needle. In a table, like the one shown below, record your observations of the reaction (both direction and maximum magnitude) of the galvanometer needle. Try to use consistent slow and fast speeds.

Direction of motion	Speed of motion	Galvanometer reading (size and direction)
1. Perpendicular to field, inward	slow	
2. Perpendicular to field, outward	slow	
3. Perpendicular to field, inward	fast	
4. Perpendicular to field, outward	fast	
5. Parallel to field, N- pole to S-pole	slow	
6. Parallel to field, S-pole to N-pole	slow	
7. Parallel to field, N-pole to S-pole	fast	
8. Parallel to field, S-pole to N-pole	fast	

Part 2

1. Note that the actual length of the conductor inside the field depends on the number of turns of wire that form the coil. Thus the effective length of wire for the coil with 10 turns is twice that of the coil with 5 turns.

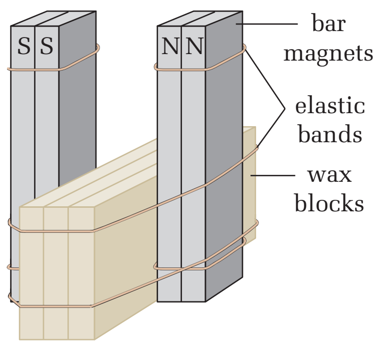
2. Examine the response of the galvanometer to each of the tests you did in Part 1. Using your observations from Part 1, move each of the coils, in turn, through the field in directions that had significant responses. (For example, if both perpendicular and parallel motions affected the current in the coil, then continue to test the effect of both of these motions throughout the experiment.)

3. Try to make the speed of all the coils as consistent as you can as you move them through the field. Observe the reaction of the galvanometer for each of the trials you perform, and record your observations in a table like the one below.

Direction of movement of the coil	Number of turns	Galvanometer reading (size and direction)

Part 3

1. To test the effect the strength of the magnetic field has on the induced current, the number of magnets used to create the field will be increased. Use elastic bands to hold two bar magnets with "like" poles together. Position two sets of these magnets so that they are aligned with the N-poles of one facing the S-poles of the other. Make sure that the gap between the poles is the same as in the previous trials (see the diagram below).



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2. Move the coil with 20 turns within the gap between the magnets, using the same orientations as in Part 2. Try to keep the speeds and orientations of the coils as constant as possible between trials. Record your observations in a table similar to the one below.

Direction of movement of the coil	Number of magnets	Galvanometer reading (size and direction)

3. Now, use an elastic band to hold three magnets together, just as you did in step 1 of this part of the investigation, and repeat step 2.
4. Use one magnet only on each side of the field, and repeat step 2.

Analyze and Conclude

1. How did moving the coil (a) perpendicularly to the field, and (b) parallel to the field affect the induced current?
2. How did the speed of the coil affect the induced current?
3. How did the length of the conductor (number of turns) affect the induced current?
4. How did the strength of the magnetic field affect the induced current in the coil? (**Note:** Do not assume that the field from two pairs of magnets doubles the field strength.)
5. In summary, briefly describe the factors that affect the strength and direction of the induced current in a conductor moving through a magnetic field.

PHYSICS & SOCIETY

TARGET SKILLS

- **Conducting research**
- **Communicating results**

MRI Technology

Jillian was diagnosed with a brain tumour at age four. While most of the tumour could be removed by surgery, some of it was too deeply imbedded in her brain stem for removal. The doctors decided that they would need to monitor these cells for any sign of growth.

X-rays do not produce good detailed images of soft tissues. Instead, magnetic resonance imaging (MRI) is used. An MRI machine is just a large doughnut-shaped electromagnet. The nuclei of the hydrogen molecules in our tissues act like tiny magnets and become aligned with the magnetic field of the MRI machine. When these nuclei are subjected to low-energy radio waves, they are nudged out of alignment. When the radio waves are turned off, the nuclei snap back into alignment and give off a tiny electromagnetic pulse. Computer analysis transforms these pulses into detailed images of the tissue. Each image is a thin cross-section, so a series of these cross-sections creates a three-dimensional picture. Images show that, over the years, Jillian's tumour has not grown.

Going Further

Medical imaging methods include MRI, fluoroscopy, CT scans, ultrasound, and fibre-optics. Investigate these techniques and their uses.

Right-hand Rules for the Generator Effect

The generator effect can be explained in terms of the motor effect. Consider a conductor in the form of a straight rod, connected to a galvanometer, oriented in a magnetic field so that the rod is at right angles to the lines of force. Now, move the conductor so that it moves through the magnetic field in a direction perpendicular to both the lines of force and the orientation of the rod (Figure 16.24).

To find the direction of the induced current, Faraday devised a method using the right-hand rule in the same way as in the motor effect. He assumed that as the conducting rod moves upward through the field, each positive charge in the rod can be considered as a tiny bit of a current that is moving in the direction of the motion of the rod. Thus, by the motor effect, each charge moving within the conductor experiences a force (***F***) that acts at right angles to both the direction of the velocity (***v***) of the rod carrying the charges, and the lines of the magnetic field (***B***). In Figure 16.24, the magnetic field points into the page as the rod moves upward through the page. According to the right-hand rule, the direction of the force on the positive charges in the rod, and thus the current that is induced in the rod, is from right to left.

This application of the right-hand rule can be used to find the direction of the induced current in the coil as it moves through a magnetic field. In Figure 16.23(a) on page 782, the magnet is being moved upward toward the coil. As it approaches the coil, the field lines curling outward from the magnet cut across the conductor.

To apply the right-hand rule, Faraday had to assume instead, that the conductor was moving downward toward the field. As the field lines from the magnet loop around from the N-pole to the S-pole, the coil passes through the field so that the coil cuts across the field lines. The detail in Figure 16.25 on the next page shows the direction of the motion of the coil, the direction of the field lines,

ELECTRONIC LEARNING PARTNER

Go to your Electronic Learning Partner for an interactive activity on electromagnetic induction.

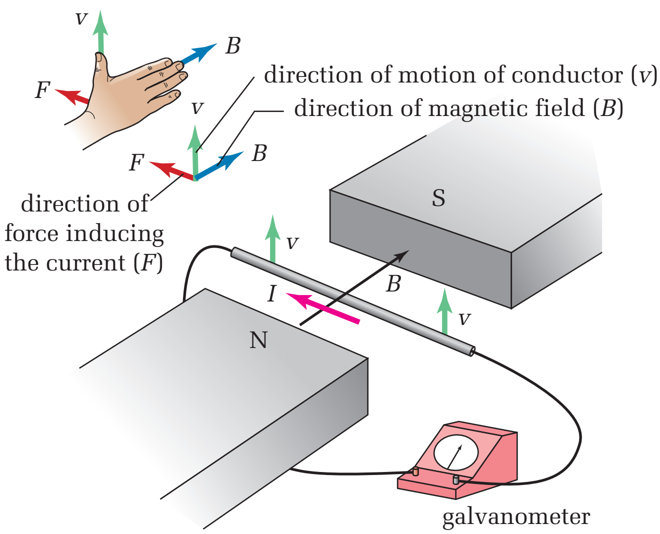


Figure 16.24 The charges in a moving conductor experience a force that pushes them along the length of the conductor to induce a current. The right-hand rule can be used to find the direction of the force on the charges that form the induced current.

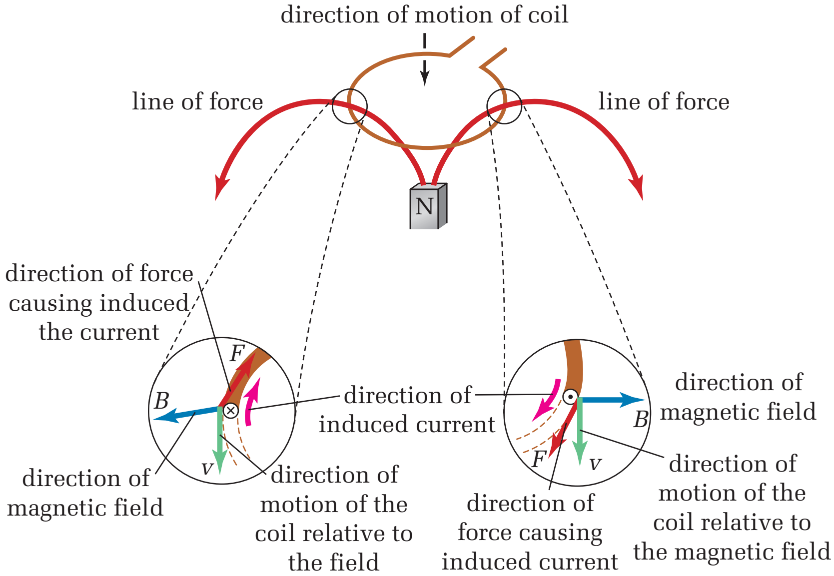


Figure 16.25 To use the right-hand rule to find the direction of the current induced in a conductor, the motion of the conductor with respect to the magnetic field must be identified.

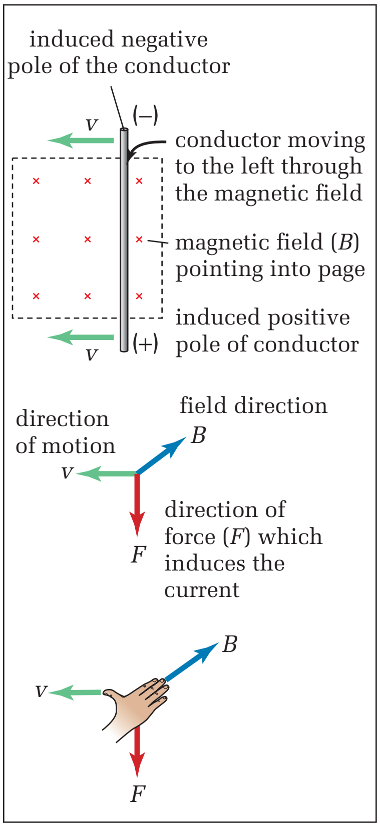


Figure 16.26 If an isolated conductor moves across a magnetic field, the generator effect induces the ends of the conductor to take on a polarity similar to a battery.

and the direction of the resulting force that causes the induced current. On the right edge of the coil, the direction of the force (induced current) is out of the page. If viewed from above, the current in the coil would be flowing clockwise.

Electromotive Force

Until now, all discussion of electromagnetic induction has centred on the induced current. Since the motor effect was based on the presence of a current, it seemed natural to base the generator effect on currents as well. However, it turns out that it is more productive to discuss electromagnetic induction in terms of the electromotive force (*emf*) produced by the motion of the conductor in the circuit rather than the current.

If a rod is connected to a complete circuit, such as in Figure 16.24, then a current will be induced in the direction as shown. However, if the rod is not connected to an external circuit, the motor force on the charges within the rod still exist. The effect of the motor force is to push the charges in the rod toward the ends of the rod (Figure 16.26). Positive charges are pushed to the end of the rod in the direction of the motor force, while negative charges are pushed in the opposite direction. This action results in one end of the rod becoming positively charged and the other end becoming negatively charged. The ends of the rod, like the poles of a battery, now have a potential difference.

The action of the electromagnetic forces on the charges in a moving conductor parallels the electrochemical action inside a battery. In both cases, positive charges are moved onto the anode, leaving the cathode with a negative charge. In both cases, the potential difference between the anode and cathode can be used to move a current externally from the anode to the cathode.

In Chapter 15, you learned that if a battery is not connected to an external circuit, the potential difference is defined as the *emf*. When the battery supplied a current to a circuit, the terminal voltage was lower than the *emf* since some of the *emf* was used to move the current through the battery's internal resistance.

Like the *emf* of a battery, the induced *emf* (measured in volts) is independent of the internal resistance, since it is calculated when there is no current. Just like the motor force (see Section 16.2), the induced *emf* varies directly as the magnetic field intensity (***B***); the velocity of the conductor through the field (***v***); and the length (***L***) of the conductor in the magnetic field.

As expected, the product of the units for these three quantities produces the units for *emf* (volts).

$$emf = vB_{\perp}L$$

$$\text{unit} = \left(\frac{\text{m}}{\text{s}}\right)(\text{T})(\text{m})$$

$$\text{unit} = \left(\frac{\text{m}}{\text{s}}\right)\left(\frac{\text{N}}{\text{A} \cdot \text{m}}\right)\text{m}$$

$$\text{unit} = \frac{\text{N} \cdot \text{m}}{\text{A} \cdot \text{s}}$$

$$\text{unit} = \frac{\text{J}}{\text{C}}$$

$$\text{unit} = \text{V}$$

Once the induced *emf* of a system has been found, then the induced current in a circuit of known resistance can be calculated using Ohm's law, in the same way as for a battery-driven circuit.

The polarity of the conductor moving through the field can be found if you use the right-hand rule for the generator effect. The thumb points in the direction of the motion of the conductor, the fingers point in the direction of the field, and the palm pushes charges toward the positive pole of the conductor.

AC Generators

Until now, only the linear motion of conductors through magnetic fields has been discussed. This type of motion does allow for sustained current production; however, the solution to that problem has already been presented. Just as the electric motor produces a continuous rotation of a coil that carries a current inside a magnetic field, the electric generator produces a continuous current from a coil that rotates in a magnetic field. In fact, the two devices are essentially the same design.

In Figure 16.27, a rectangular coil is rotating counter-clockwise in the magnetic field, which points from right to left. The right edge of the coil is moving upward through the magnetic field. By the right hand rules, the *emf* in the right edge of the coil has its positive end nearest the viewer. On the left edge of the coil, which is moving downward, the positive end of its edge is farthest from the viewer. The *emf*s for the edges of the coil are like cells in

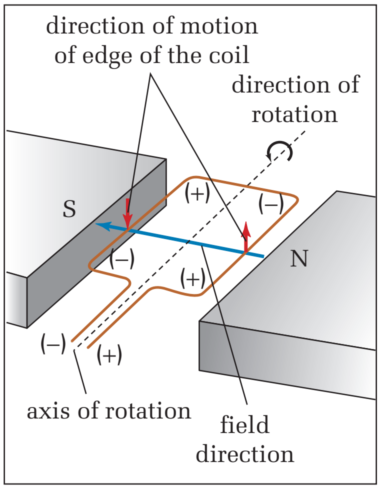
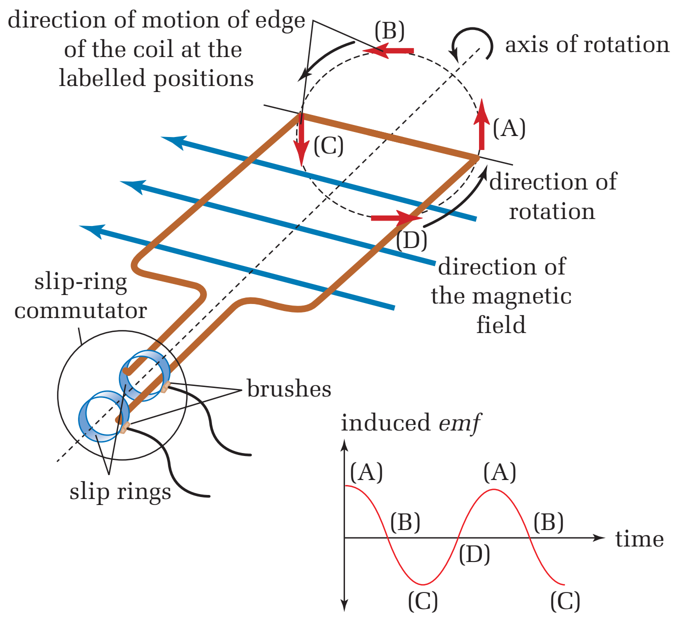


Figure 16.27 When a coil is rotated in a magnetic field, the edges of the coil cut the magnetic lines of force to induce an *emf* in the coil.

Figure 16.28 When the armature of a generator is rotated between the poles of the field magnets, an alternating *emf* is produced.



series. They add together to produce an *emf* for each loop of the coil that is twice the *emf* of a single edge. Each turn of the coil adds two more edges in series, so that the total *emf* for the generator is the *emf* of each turn multiplied by the number of turns. This makes it possible to design generators that produce any desired *emf*.

An **AC generator** has an armature, which is a copper coil wound around an iron core. As in an electric motor, the magnetically permeable iron core inside the coil greatly enhances the strength of the field inside the coil. When the armature is rotated, the edges of the coil cut across the field lines of the magnetic field to produce an induced current in the coil. Like the motor, the current in the coil is transferred to the fixed body of the generator by brushes sliding on a **slip-ring commutator** (Figure 16.28). This consists of two unbroken brass or copper rings.

Using a slip-ring commutator, rather than a split-ring commutator, means that the brushes are always in contact with the same end of the coil. When the right edge of the coil is moving upward through the field (position A in the diagram), the slip ring nearest the viewer is the positive end of the coil. However, on the other half of the rotation, when the same edge is moving downward (through position C), the slip ring farthest from the viewer is positive.

Even though the coil is rotating at a constant speed, the induced *emf* is not constant. The edges of the coil cut across the lines of force at the greatest speed when they are moving at right angles across the lines of force. This occurs when the edges of the coil are at positions A and C in the diagram. When the edges of the coil are passing through those positions, the induced *emf* in the coil is the greatest.

PHYSICS FILE

Since copper is diamagnetic, it is not attracted or repelled by magnets at room temperatures unless the magnets are very powerful. This property makes copper an ideal material for exploiting or investigating electromagnetism. For example, if steel rather than copper wire had been used to investigate the motor effect in Chapter 14, there would have been little to observe. Because steel is ferromagnetic, the steel wire would have been strongly attracted toward the poles of the magnet so that the force of the magnetic field on the current in the wire would have gone unnoticed. On the other hand, a conductor made of copper does not interact directly with the magnet; therefore, the only observable effect was the motor force. The same is true for the generator effect.

As the edges of the coil move through positions B and D in Figure 16.28, they are moving parallel to the lines of force. Since, at that instant, the edges are not cutting any lines of force, the induced *emf* is zero. At positions B and D, the edges of the coil are in the process of reversing their directions of motion through the field. The edge that was moving up on the right side is now starting to move down on the left side and vice versa. As the directions of the edges of the coil reverse, so does the direction of the induced *emf* in the coil, resulting in an AC generator. The actual speed at which the edges of the coil cut the lines of force varies as the sine of the angle between the direction of the lines of force, and the direction of the motion of the edge. Thus, AC generators produce the characteristic sine wave pattern of AC electricity.

DC Generators

As you saw in Section 16.2, in the DC motor, a split-ring commutator is used to convert the incoming DC current into an AC current in the motor coil. Similarly, in a **DC generator**, a split-ring commutator is used to replace the slip-ring commutator. As the coil rotates, the induced current reverses in the coil. At the same instant that the current changes direction in the coil, the brushes cross the gap from one half of the split ring to the other half, so that the current always leaves the generator in one direction. The current still increases and decreases depending on the angle at which the edges of the coil cut through the magnetic field. Thus, the sine wave output of the AC generator is converted into a pulsating DC output (Figure 16.29). This type of current is referred to as a **rectified** (made upright) **DC current**.

PROBEWARE

www.mcgrawhill.ca/links/atlphysics

If your school has probeware equipment, go to the Internet site above and follow the links for a laboratory activity on induced electric current.

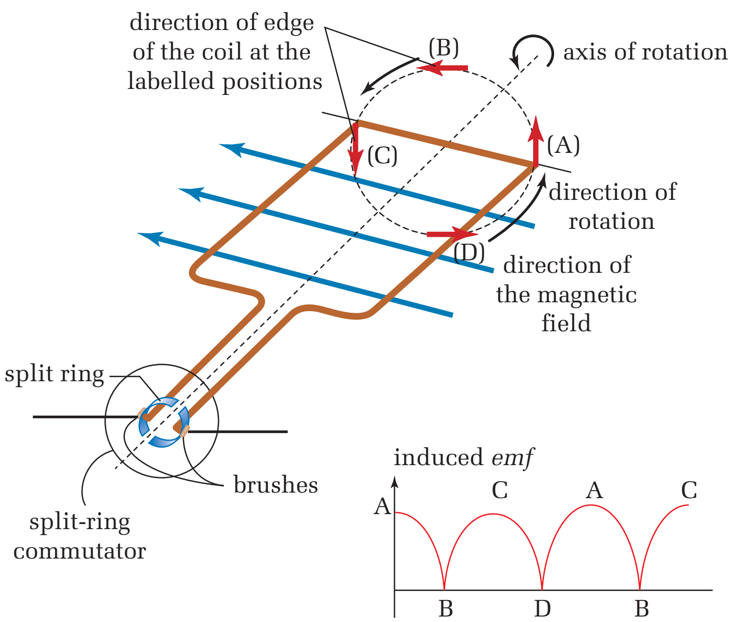


Figure 16.29 The split-ring commutator in a DC generator rectifies the output of an AC generator to produce a pulsating DC output.

Alternators

Every time the brush of a DC generator crosses over from one half of the split-ring commutator to the other, a tiny electric arc is formed. Eventually, this will cause the brushes to fail. Since the brushes on a slip-ring commutator slide continuously on the same ring, they last much longer than the brushes on a split-ring commutator. Today, the **alternator**, a device that uses diodes to rectify the output of an AC generator, is more common than DC generators.

Lenz's Law

To find the direction of the induced current using the right-hand rule and the motor effect, as in Figure 16.24 (page 787), is sometimes quite difficult. This is especially true when there is no apparent motion of the coil relative to the lines of force. An obvious example of this occurs in Faraday's original experiment with the coils wrapped around the iron ring. In 1834, a Russian physicist, Heinrich Lenz (1804–1865), devised an alternate method of finding the direction of the induced current.

Lenz realised that when Faraday moved the bar magnet through the coil (Figure 16.23, page 782), he was generating electrical energy in the form of the induced current. By the law of conservation of energy, the gain in electrical energy had to come from the kinetic energy of the magnet moving through the coil. The transfer of energy from one object to another is, by definition, work. Work, in turn, requires a force. To remove kinetic energy from the magnet requires a force that acts in the opposite direction to the motion of the magnet. If the magnet could move unimpeded through the coil, then no work would be required to create the electrical energy. Lenz argued that, by the law of conservation of energy, whenever a conductor interacts with a magnetic field, there must be an induced current that opposes the interaction. This conclusion is known as **Lenz's law**.

LENZ'S LAW

When a conductor interacts with a magnetic field, there must be an induced current that opposes the interaction, because of the law of conservation of energy.

Figure 16.30 Electric guitar pickups rely on Lenz's law.

The pickup of an electric guitar, shown in Figure 16.30, is made of a permanent magnet surrounded by a tiny coil of wire. When the ferromagnetic metal string of an electric guitar is plucked, its motion near the magnetic field of the pickup causes the strength of the magnetic field inside the coil to fluctuate. By Lenz's law, a very weak current, whose magnetic field opposes the variations in magnetic field strength produced by the vibrating string, is induced in the coil. The current is then amplified and sent to a loudspeaker that converts the current back into sound.

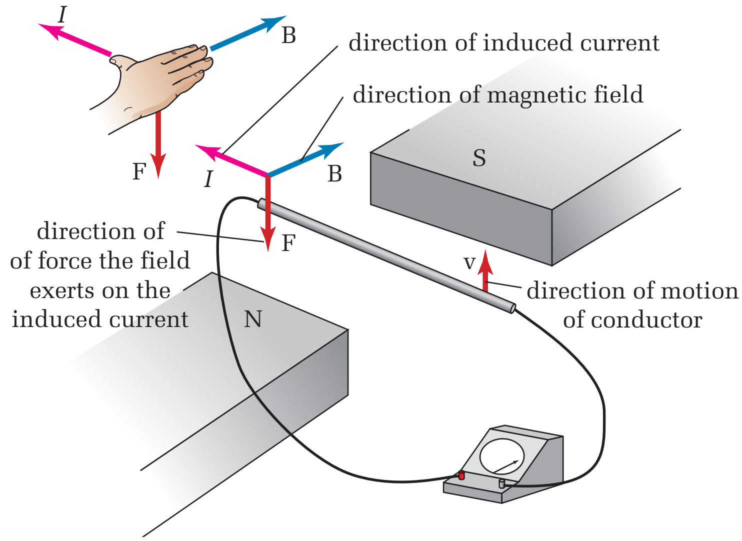


Figure 16.31 The direction of the force exerted by the magnetic field on an induced current is opposite to the motion of the conductor through the magnetic field.

Re-examine the system in Figure 16.24 in light of Lenz's law. Firstly, recall that for the generator effect, the right-hand rule was applied in the following manner: the thumb indicated the motion of the conductor through the field; the fingers were pointed in the direction of the lines of force; and the palm pushed in the direction of the force on the positive charges in the conductor, and thus in the direction of the induced current. In Figure 16.24, this indicated that the induced current would move from right to left.

In contrast, Lenz's law states that the direction of the force the magnetic field exerts on the induced current must oppose the direction of the motion of the conductor. To apply the right-hand rule with Lenz's law, point your fingers in the direction of the lines of force and orient your palm to exert a force that opposes the motion of the conductor through the field (Figure 16.31). The thumb then must be pointing in the direction of the induced current.

In the previous case, there does not seem to be much advantage to using Lenz's law over the generator effect. But look back at how the generator effect was used in Figure 16.25 (page 788). In this case, a variation of right-hand rule #2 can be used to simplify finding the direction of the induced current in a coil or solenoid.

According to Lenz, as the bar magnet is moved upward toward the centre of the coil, the motion of the magnetic field must induce a current in the coil that interacts with the field to oppose the motion of the magnet. Since the N-pole of the magnet is approaching the coil, the induced current creates a magnetic field inside the coil with field lines that point downward, pushing the N-pole of the magnet away from the coil.

The direction of the magnetic field for a coil is found using right-hand rule #2. Place your fingers along the edge of the coil in the direction of the current, and your thumb will point in the direction of the field lines inside the coil. In this case, you want the magnetic field to point downward so that the N-pole of the magnet experiences a force downward. Place the fingers of your right hand along the edge of the coil so that your thumb points downward (the direction of the magnetic field through the coil). Your fingers lie along the edge of the coil in the direction of the induced current (Figure 16.32(A)).

When the N-pole of the magnet, positioned below the coil, is moved away from the coil, Lenz's law states that the magnetic field from the induced current still opposes the motion. To stop the N-pole moving away from the coil, it must try to pull the N-pole of the magnet toward the coil. The N-pole of a magnet experiences a force in the direction of the field acting on it, thus the magnetic field inside the coil would have to be directed upward. Placing your fingers along the edge of the coil, so that the thumb is pointing upward, gives the direction of the induced current in the loop (Figure 16.32(B)).

If the coil in Figure 16.32 had not been connected to the galvanometer, then the ends of the coil would have gained positive and negative charges like the anode and cathode of a battery. The end of the coil to which the current flowed would have become the anode.

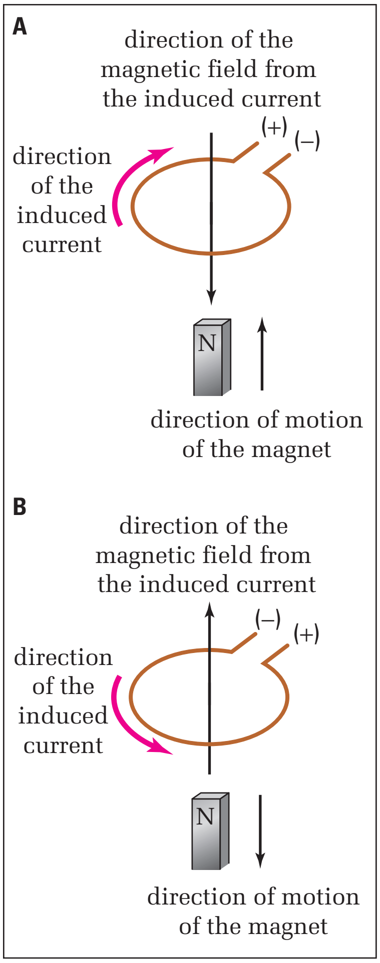


Figure 16.32 When a conductor and a magnet move in relation to each other, by Lenz's law, the induced current creates a magnetic field that opposes the motion.

Back *emf*

When an electric motor is switched on, the magnetic field around the armature exerts a force on the current in the coils. This force causes the armature to rotate within the magnetic field. As long as a current flows through the coils, the magnetic field exerts a force on the armature. However, if forces cause accelerations, why does the armature of the motor not continue to accelerate to an increasingly faster rate of rotation? It should not be too surprising to find that the answer is found in Lenz's law.

As the armature speeds up, its coil is moving through the magnetic field that drives the motor. However, the generator effect states that the motion of the coil in the field must result in an induced *emf*. Lenz's law says that the direction of the induced *emf* (and induced current) must oppose the *emf* (and the current) supplied by the battery.

Once again, consider the simple case of a single conductor inside a magnetic field. The conductor is connected to a battery (Figure 16.33, page 795). The battery causes a current in the conductor from left to right. The right-hand rule for the motor force indicates that the direction of the force on the conductor is toward the top of the page. If this conductor is free to move, it will move in that direction.

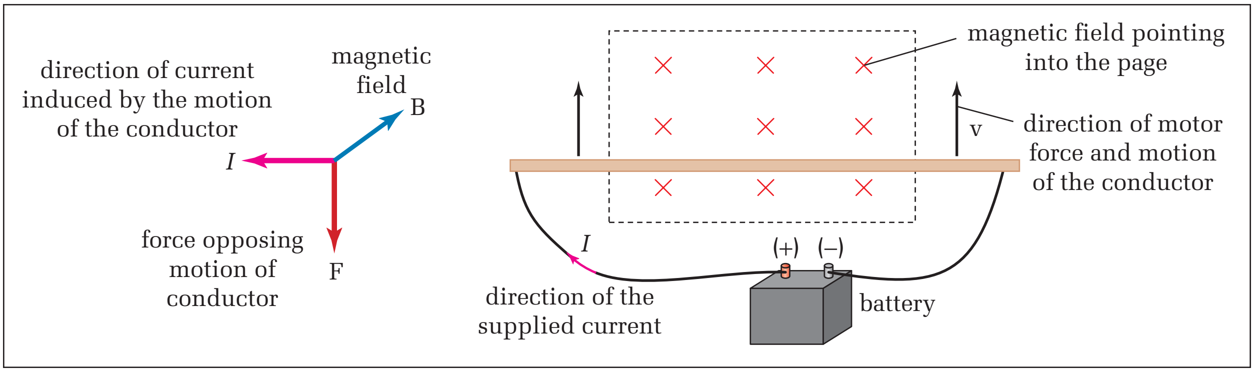


Figure 16.33 As the current from the battery experiences the motor effect, the motion of the conductor in the field induces a back *emf* that opposes the supplied *emf*.

As soon as the conductor begins to move upward, the generator effect begins. By Lenz's law, the motion of the conductor, toward the top of the page through a magnetic field into the page, results in an *emf* across the conductor that pushes a current from right to left, opposing the current from the battery. This is defined as the **back *emf***. As the conductor speeds up, the back *emf* increases. In the absence of friction, the speed of the conductor would increase until the back *emf* equalled the supplied *emf* from the battery. At that point, the net *emf* (and thus the net current through the conductor) would be zero, and the conductor would be moving in equilibrium at a constant speed.

When a motor begins to run, the rate at which the armature rotates continues to increase until equilibrium is reached. Since there is always friction, the top speed of the armature is such that the back *emf* is a bit smaller than the *emf* of the battery. This leaves a net *emf* that causes just enough current through the armature so that the forward force of the motor effect equals the drag of the force of friction. The armature is now in dynamic equilibrium, and moves at a constant speed.

If the load on a motor is increased, then the rate of rotation of the armature slows down. As it slows down, the back *emf* is reduced and the net *emf*, in the forward direction, increases. The armature continues to slow down until the net current through the coils increases enough so that motor force on the resulting current is sufficient to drive the increased load.

Eddy Currents and Magnetic Damping

Magnetic damping is a common application of Lenz's law. Sensitive balances, such as the equal triple-beam balances or electronic balances used in laboratories, would require considerably more time to come to rest if they were not magnetically damped (slowed down). A flat plate of diamagnetic or paramagnetic material (copper or aluminum) is attached to the arm of the scale so that it is inside a magnetic field (Figure 16.34). As the arm of the scale moves up and down, the magnetic field induces **eddy currents** (small circular currents) within the plate.

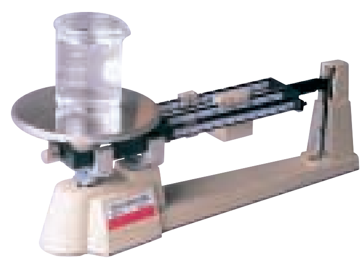


Figure 16.34 The motion of the arm in the triple-beam balance results in eddy currents in the plate at the end of the arm. By Lenz's law, the energy to cause the eddy currents must come from the kinetic energy of the arm, damping its motion.

By Lenz's law, the direction of the eddy currents is such that the motor force on them opposes the motion of the plate, slowing down the motion of the arm. As the motion of the arm slows down, the damping effect of the eddy currents is reduced so that the final position, and thus the accuracy of the scale, is not affected.

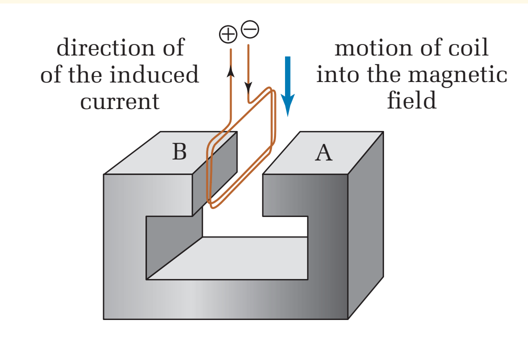
Go back to Investigation 16-E. Can you explain your observations in terms of Lenz's law and the law of conservation of energy?

16.3 Section Review

1. K/U A conductor is oriented horizontally parallel to the north-south direction. It is moving eastward through a magnetic field that points directly downward. In which direction does the induced current flow through the conductor?

2. K/U A loop of wire lies in the horizontal plane. A bar magnet, with its S-pole pointing downward, is lowered into the loop from above. As seen from above, in which direction will the induced current move around the loop?

3. K/U A coil is dropped into the magnetic field between the poles of a horseshoe magnet. If the current in the coil is in the direction indicated, which pole of the magnet (A or B) is its N-pole?



4. K/U A coil of wire lies in the same plane as the page. The pole of a bar magnet is moved toward the coil along the axis of the coil. The induced current resulting from the motion of the magnetic field is clockwise around the coil. Which pole of the magnet approached the coil?

5. C Use Lenz's law to answer the first four questions. Compare how you applied Lenz's law and the right-hand rule interpretation of the generator effect. For each question, compare how the right-hand rule applies using the generator effect, and how it applies using Lenz's law.

6. K/U A coil lies in the plane of the page. When a bar magnet moves toward the coil, along the axis of the coil from behind the page, a current is induced in the coil in a counter-clockwise direction. Which pole of the magnet is approaching the coil?

7. C Draw a diagram of a plate, lying in the plane of the page, and moving towards the bottom of the page, so that it will pass through a magnetic field that points directly out of the page. Apply Lenz's law to determine the direction of the eddy current that will act to damp the motion of the plate. Hint: It may help to analyze the induced currents in the plate when the eddy is just entering and leaving the field.

UNIT PROJECT PREP

- Lenz's law predicts the effect of the back *emf* on an electric motor.
- What is the effect of the back *emf* on the motion of an electric motor?
- To what extent should you be aware of eddy currents and magnetic damping within your motor design?