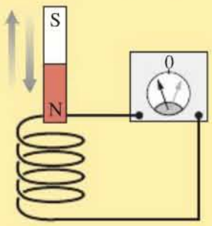
25 EM Induction and EM Waves

The photo of the flower on the left shows how it appears to our eyes, in visible light. But there's more to the story! The false-color view of the flower on the right shows its appearance in the ultraviolet, beyond the range of human vision, revealing pigments we can't see. Whose eyes are these pigments intended for?

LOOKING AHEAD ▸▸

The goal of Chapter 25 is to understand the nature of electromagnetic induction and electromagnetic waves.

Connecting Electric and Magnetic Phenomena



Moving a magnet into or out of a coil of wire creates a momentary current in the wire. The changing *magnetic* field creates an *electric* current in the coil, an example of the close connection between electric and magnetic phenomena we explore in this chapter.

This chapter will draw on all that we have learned about electricity and magnetism. You should especially review these sections:

Looking Back ◂◂
20.4 The electric field
21.4 The electric potential
24.2–24.6 Magnetic fields and forces

Induced emf and Induced Currents

A *changing* magnetic field creates an emf—which can create a current in a conductor. An emf produced this way is called an **induced emf**; the resulting current is called an **induced current.**

Shaking a magnet back and forth through a coil induces a current that runs the flashlight.

Turning blades rotate a coil of wire in a magnetic field. This change induces enough current to power many homes.

A rapidly changing magnetic field from the base unit induces a current in a coil inside the phone, charging it with no wire connection.

Electromagnetic Waves

The connection between electricity and magnetism is seen most clearly in the existence of **electromagnetic waves,** traveling waves of electric and magnetic fields.

The metal bars on this antenna detect the vertical electric field of an electromagnetic wave.

Everything you've learned about waves applies to electromagnetic waves.

Looking Back ◂◂
15.3–15.5 Basic wave concepts, light waves, plane waves, intensity

The Electromagnetic Spectrum

You are already familiar with electromagnetic waves: Radio waves, microwaves, light waves, and x rays are all electromagnetic waves with different wavelengths. We'll explore the **spectrum** of possible waves.

Long-wavelength microwaves rotate water molecules in food.

The vibrations of atoms in the filament emit visible light.

Very-short-wavelength x rays act rather like particles that we'll call **photons.**

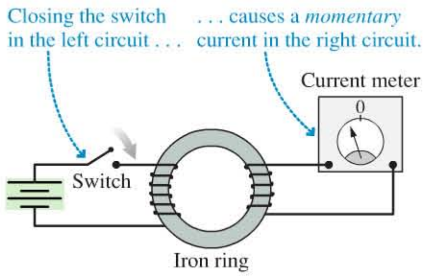
25.1 Induced Currents

In Chapter 24, we learned that a current can create a magnetic field. As soon as this discovery was widely known, investigators began considering a related question: Can a magnetic field create a current?

One of the early investigators was Michael Faraday, who was experimenting with two coils of wire wrapped around an iron ring, as shown in **FIGURE 25.1**, when he made a remarkable discovery. He had hoped that the magnetic field generated by a current in the coil on the left would create a magnetic field in the iron, and that the magnetic field in the iron might then somehow produce a current in the circuit on the right.

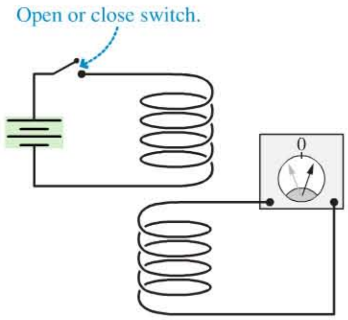
This technique failed to generate a steady current, but Faraday noticed that the needle of the current meter jumped ever so slightly at the instant when he closed the switch in the circuit on the left. After the switch was closed, the needle immediately returned to zero. Faraday's observation suggested to him that a current was generated only if the magnetic field was *changing* as it passed through the coil. Faraday set out to test this hypothesis through a series of experiments.

FIGURE 25.1 Faraday's discovery of electromagnetic induction.



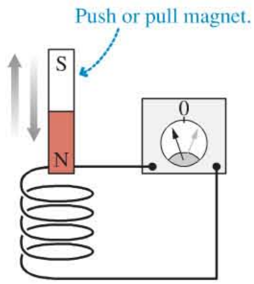
Faraday investigates electromagnetic induction

Faraday placed one coil directly above the other, without the iron ring. There was no current in the lower circuit while the switch was in the closed position, but a momentary current appeared whenever the switch was opened or closed.



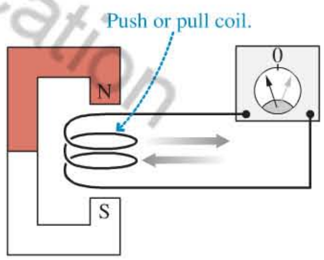
Opening or closing the switch creates a momentary current.

Faraday pushed a bar magnet into a coil of wire. This action caused a momentary deflection of the needle in the current meter, although *holding* the magnet inside the coil had no effect. A quick withdrawal of the magnet deflected the needle in the other direction.



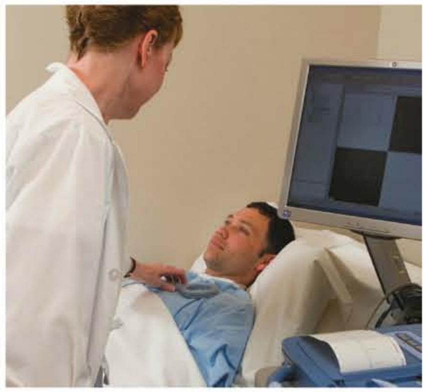
Pushing the magnet into the coil or pulling it out creates a momentary current.

Must the magnet move? Faraday created a momentary current by rapidly pulling a coil of wire out of a magnetic field, although there was no current if the coil was stationary in the magnetic field. Pushing the coil *into* the magnet caused the needle to deflect in the opposite direction.



Pushing the coil into the magnet or pulling it out creates a momentary current.

All of these experiments served to bolster Faraday's hypothesis: **Faraday found that there is a current in a coil of wire if and only if the magnetic field passing through the coil is *changing.*** It makes no difference what causes the magnetic field to change: current stopping or starting in a nearby circuit, moving a magnet through the coil, or moving the coil into and out of a magnet. The effect is the same in all cases. There is no current if the field through the coil is not changing, so it's not the magnetic field itself that is responsible for the current but, instead, it is the *changing of the magnetic field.*



▶ **External pacemaker programming** BIO A circuit that creates a changing magnetic field can induce a current in a second circuit with no direct electrical connection to the first. In this photo a coil carrying an alternating current creates a changing magnetic field that induces currents in a sensing circuit in a cardiac pacemaker inside the patient's chest. These currents adjust settings for the pacemaker. The magnetic fields can penetrate the body so the pacemaker can be programmed with no need for surgery.

The current in a circuit due to a changing magnetic field is called an **induced current.** Opening the switch or moving the magnet *induces* a current in a nearby circuit. An induced current is not caused by a battery; it is a completely new way to generate a current. The creation of an electric current by a changing magnetic field is our first example of **electromagnetic induction.**

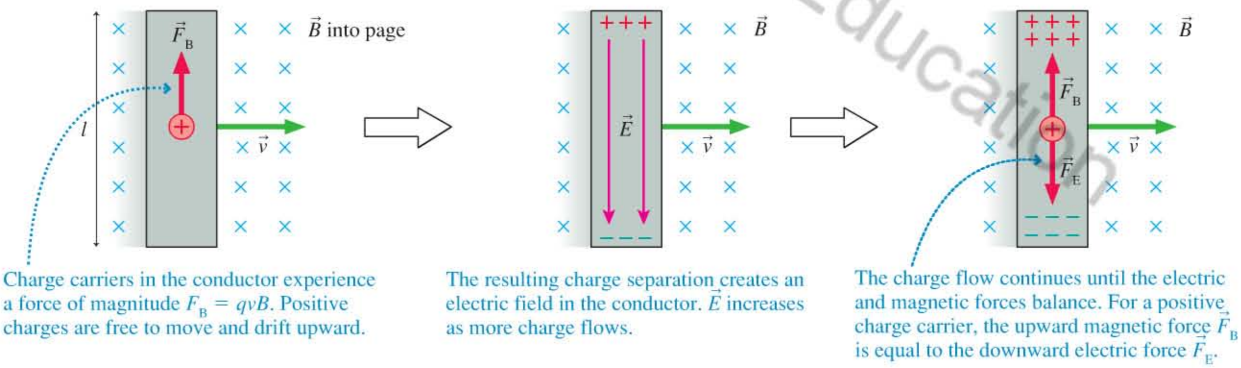
A satellite tethered to the Space Shuttle.

25.2 Motional emf

In 1996, astronauts on the Space Shuttle deployed a satellite at the end of a 20-km-long conducting tether. A potential difference of up to 3500 V developed between the shuttle and the satellite as the wire between the two swept through the earth's magnetic field. Why would the motion of a wire in a magnetic field produce such a large voltage? Let's explore the mechanism behind this *motional emf.*

To begin, consider a conductor of length l that moves with velocity $\vec{v}$ through a uniform magnetic field $\vec{B}$, as shown in FIGURE 25.2. The charge carriers inside the conductor—assumed to be positive, as in our definition of current—also move with velocity $\vec{v}$, so they each experience a magnetic force. For simplicity, we will assume that $\vec{v}$ is perpendicular to $\vec{B}$, in which case the magnitude of the force is $F_B = qvB$. This force causes the charge carriers to move. For the geometry of Figure 25.2, the right-hand rule tells us that the positive charges move toward the top of the moving conductor, leaving an excess of negative charge at the bottom.

FIGURE 25.2 The magnetic force on the charge carriers in a moving conductor creates an electric field inside the conductor.



This motion of the charge carriers cannot continue forever. The separation of the charge carriers creates an electric field. The resulting electric force *opposes* the separation of charge, so the charge separation continues only until the electric force has grown to exactly balance the magnetic force:

$$F_E = qE = F_B = qvB$$

When this balance occurs, the charge carriers experience no net force and thus undergo no further motion. The electric field strength at equilibrium is

$$E = vB \tag{25.1}$$

Thus, **the magnetic force on the charge carriers in a moving conductor creates an electric field $E = vB$ inside the conductor.**

The electric field, in turn, creates an electric potential difference between the two ends of the moving conductor. We found in Chapter 21 that the potential difference between two points separated by distance l parallel to an electric field E is $\Delta V = El$. Thus the motion of the wire through a magnetic field *induces* a potential difference

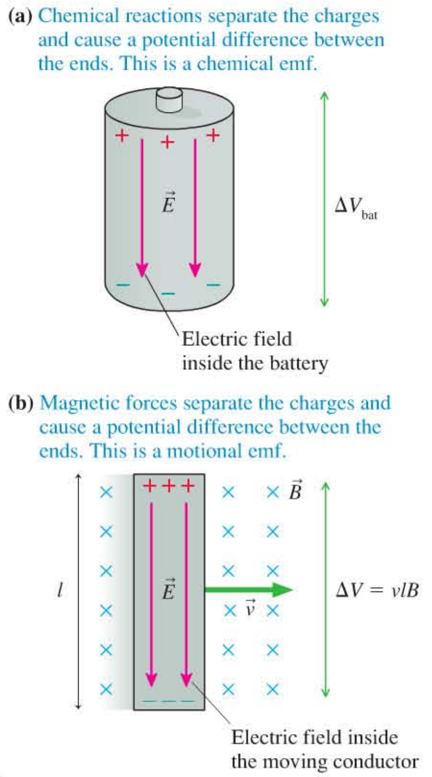
$$\Delta V = vlB \tag{25.2}$$

between the ends of the conductor. The potential difference depends on the strength of the magnetic field and on the wire's speed through the field. This is similar to the action of the electromagnetic flowmeter that we saw in the preceding chapter.

There's an important analogy between this potential difference and the potential difference of a battery. FIGURE 25.3a reminds you that a battery uses a nonelectric force—which we called the charge escalator—to separate positive and negative charges. We refer to a battery, where the charges are separated by chemical reactions, as a source of *chemical emf.* The moving conductor of FIGURE 25.3b develops a potential difference because of the work done to separate the charges. The emf of the conductor is due to its motion, rather than to chemical reactions inside, so we can define the **motional emf** of a conductor of length l moving with velocity $\vec{v}$ perpendicular to a magnetic field $\vec{B}$ to be

$$\mathcal{E} = vlB \tag{25.3}$$

FIGURE 25.3 Two different ways to generate an emf.



EXAMPLE 25.1 Finding the motional emf for an airplane

A Boeing 747 aircraft with a wingspan of 65 m is cruising at 260 m/s over northern Canada, where the magnetic field of the earth (magnitude 5.0×10^{-5} T) is directed straight down. What is the potential difference between the tips of the wings?

PREPARE The wing is a conductor moving through a magnetic field, so there will be a motional emf. We can visualize a top view of this situation exactly as in Figure 25.3b, with the wing as the moving conductor.

SOLVE The magnetic field is perpendicular to the velocity, so we can compute the potential difference using Equation 25.3:

$$\Delta V = vlB = (260 \text{ m/s})(65 \text{ m})(5.0 \times 10^{-5} \text{ T}) = 0.85 \text{ V}$$

ASSESS The earth's magnetic field is small, so the motional emf will be small as well unless the speed and the length are quite large. The tethered satellite generated a much higher voltage due to its much greater speed and the great length of the tether, the moving conductor.

▶ **A head for magnetism?** BIO Observations of hammerhead sharks imply that they navigate using the earth's magnetic field, and controlled laboratory experiments verify that they can indeed reliably detect such modest fields. How do they do it? One possibility is that they use their keen electric sense, described in Chapter 21. Sharks can detect small potential differences; perhaps they detect magnetic fields by sensing the motional emf as they move through the water. If so, the width of their oddly shaped heads would be an asset because the magnitude of the potential difference is proportional to the length of the moving conductor.

Induced Current in a Circuit

The moving conductor of Figure 25.3 had an emf, but it couldn't sustain a current because the charges had nowhere to go. We can change this by including the moving conductor in a circuit.

FIGURE 25.4 shows a length of wire with resistance R sliding with speed v along a fixed U-shaped conducting rail. The wire and the rail together form a closed conducting loop—a circuit.

Suppose a magnetic field $\vec{B}$ is perpendicular to the plane of the circuit. Charges in the moving wire will be pushed to the ends of the wire by the magnetic force, just as they were in Figure 25.3, but now the charges can continue to flow around the circuit. The moving wire acts like the battery in a circuit.

The current in the circuit is an induced current, due to magnetic forces on moving charges. In this example, the induced current is counterclockwise. The total

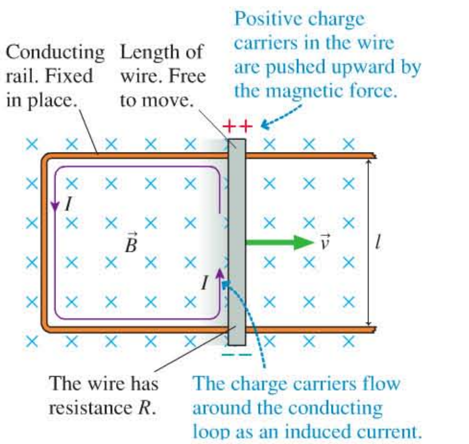
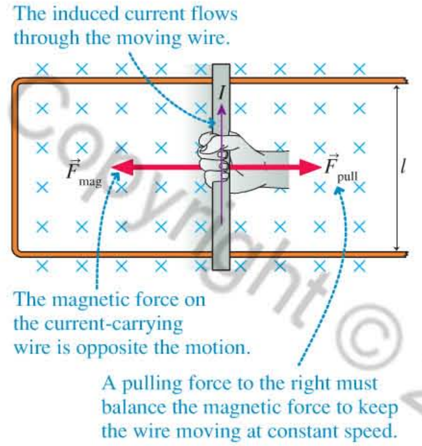


FIGURE 25.4 A current is induced in the circuit as the wire moves through a magnetic field.

FIGURE 25.5 A pulling force is needed to move the wire to the right.



resistance of the circuit is just the resistance R of the moving wire, so the induced current is given by Ohm's law:

$$I = \frac{\mathcal{E}}{R} = \frac{vlB}{R} \tag{25.4}$$

We've assumed that the wire is moving along the rail at constant speed. But we must apply a continuous pulling force $\vec{F}_{pull}$ to make this happen; FIGURE 25.5 shows why. The moving wire, which now carries induced current I, is in a magnetic field. You learned in Chapter 24 that a magnetic field exerts a force on a current-carrying wire. According to the right-hand rule, the magnetic force $\vec{F}_{mag}$ on the moving wire points to the left. This "magnetic drag" will cause the wire to slow down and stop *unless* we exert an equal but opposite pulling force $\vec{F}_{pull}$ to keep the wire moving.

NOTE ▶ Think about this carefully. As the wire moves to the right, the magnetic force $\vec{F}_B$ pushes the charge carriers *parallel* to the wire. Their motion, as they continue around the circuit, is the induced current I. Now, because we have a current, a second magnetic force $\vec{F}_{mag}$ enters the picture. This force on the current is *perpendicular* to the wire and acts to slow the wire's motion. ◀

The magnitude of the magnetic force on a current-carrying wire was found in Chapter 24 to be $F_{mag} = IlB$. Using that result, along with Equation 25.4 for the induced current, we find that the force required to pull the wire with a constant speed v is

$$F_{pull} = F_{mag} = IlB = \left(\frac{vlB}{R}\right)lB = \frac{vl^2B^2}{R} \tag{25.5}$$

Energy Considerations

FIGURE 25.6 Power into and out of an induced-current circuit.

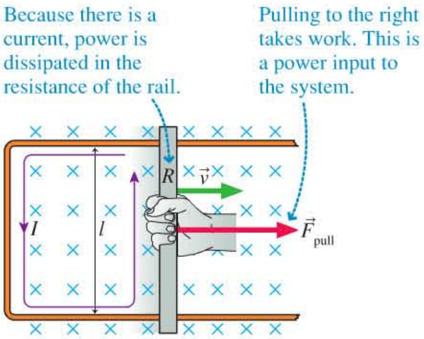


FIGURE 25.6 is another look at the wire moving on a conducting rail. Because a force is needed to pull the wire through the magnetic field at a constant speed, we must do work to keep the wire moving. You learned in Chapter 10 that the power exerted by a force pushing or pulling an object with velocity v is $P = Fv$, so the power provided to the circuit by the force pulling on the wire is

$$P_{input} = F_{pull}v = \frac{v^2l^2B^2}{R} \tag{25.6}$$

This is the rate at which energy is added to the circuit by the pulling force.

But the circuit dissipates energy in the resistance of the circuit. You learned in Chapter 22 that the power dissipated by current I as it passes through resistance R is $P = I^2R$. Equation 25.4 for the induced current I gives us the power dissipated by the circuit of Figure 25.6:

$$P_{dissipated} = I^2R = \frac{v^2l^2B^2}{R} \tag{25.7}$$

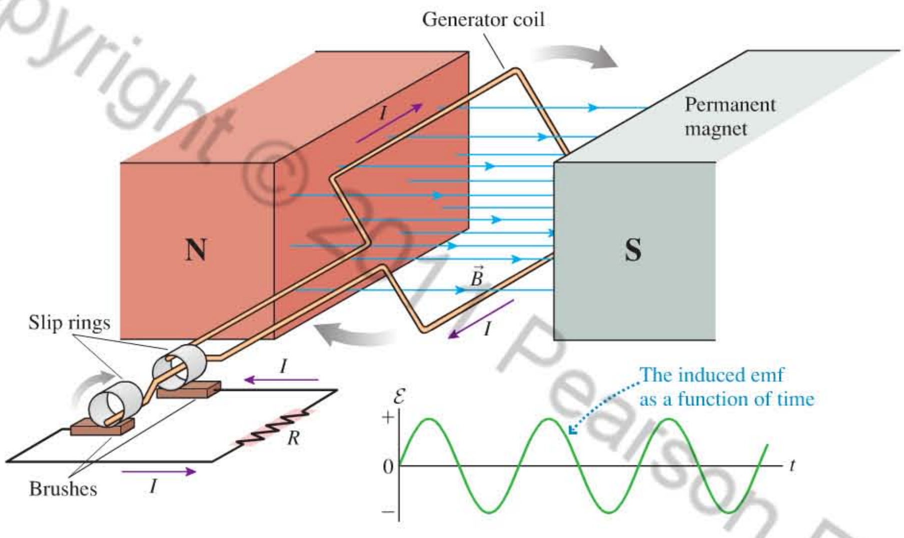
Equations 25.6 and 25.7 have identical results. This makes sense: The rate at which work is done on the circuit is exactly balanced by the rate at which energy is dissipated. The fact that our final result is consistent with energy conservation is a good check on our work.

Generators

A device that converts mechanical energy to electric energy is called a **generator.** The example of Figure 25.6 is a simple generator, but it is not very practical. Rather than move a straight wire, it's more practical to rotate a coil of wire, as in FIGURE 25.7.

As the coil rotates, the left edge always moves upward through the magnetic field while the right edge always moves downward. The motion of the wires through the magnetic field induces a current to flow as noted in the figure. The induced current is removed from the rotating loop by *brushes* that press up against rotating *slip rings*. The circuit is completed as shown in the figure.

FIGURE 25.7 A generator using a rotating loop of wire.

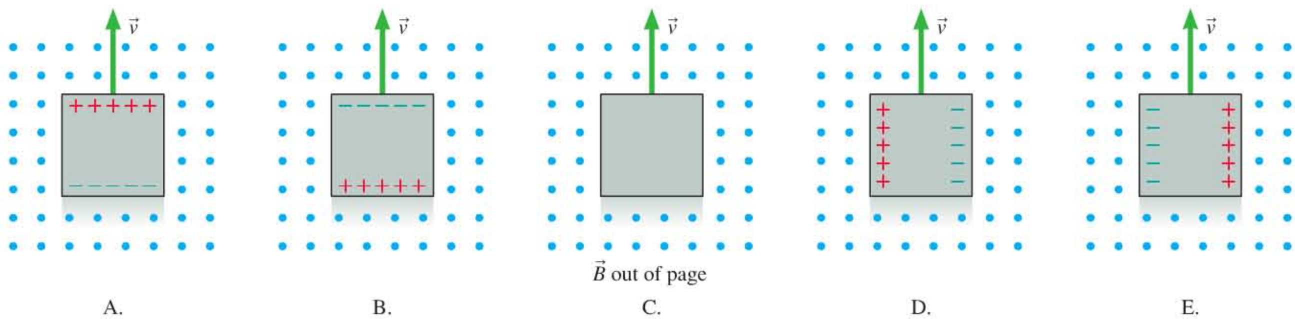


As the coil in the generator of Figure 25.7 rotates, the sense of the emf changes, giving a sinusoidal variation of emf as a function of time. Electricity is produced using generators of this sort; the electricity in your house has a varying voltage. The alternating sign of the voltage produces an *alternating current,* so we call such electricity AC. We'll have more to say about this type of electricity in Chapter 26.

TRY IT YOURSELF

No work, no light Turning the crank on a generator flashlight rotates a coil of wire in the magnetic field of a permanent magnet. With the switch off, there is no current and no drag force; it's easy to turn the crank. Closing the switch allows an induced current to flow through the coil, so the bulb lights. But current in the wire experiences a drag force in the magnetic field, so you must do work to keep the crank turning. This is the source of the output power of the circuit, the light of the bulb. Commercial generators use water flowing through a dam, wind turning a propeller, or turbines spun by expanding steam to rotate much larger coils, but the principle is the same. When you flip a switch, something, somewhere has to do a bit more work to turn a crank.

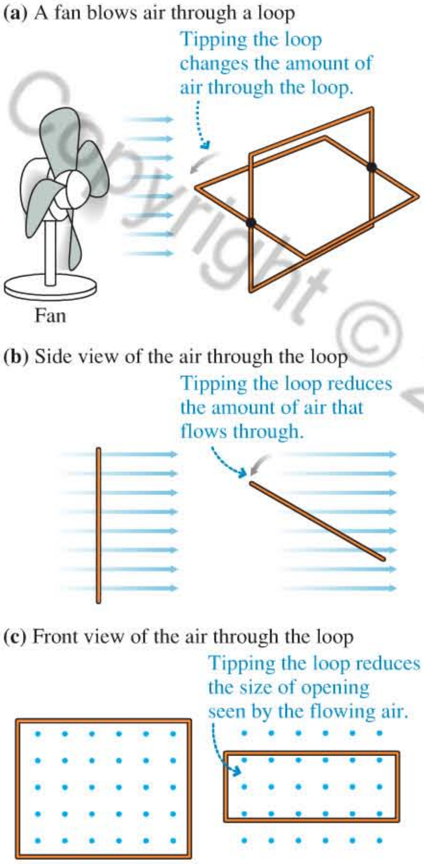
STOP TO THINK 25.1 A square conductor moves through a uniform magnetic field. Which of the figures shows the correct charge distribution on the conductor?



25.3 Magnetic Flux

We've begun our exploration of electromagnetic induction by analyzing a circuit in which one wire moves through a magnetic field. You might be wondering what this has to do with Faraday's discovery. Faraday found that a current is induced when the amount of magnetic field passing through a coil or a loop of wire

FIGURE 25.8 The amount of air flowing through a loop depends on the angle.



changes. But that's exactly what happens as the slide wire moves down the rail in Figure 25.4! As the circuit expands, more magnetic field passes through the larger loop. It's time to define more clearly what we mean by "the amount of field passing through a loop."

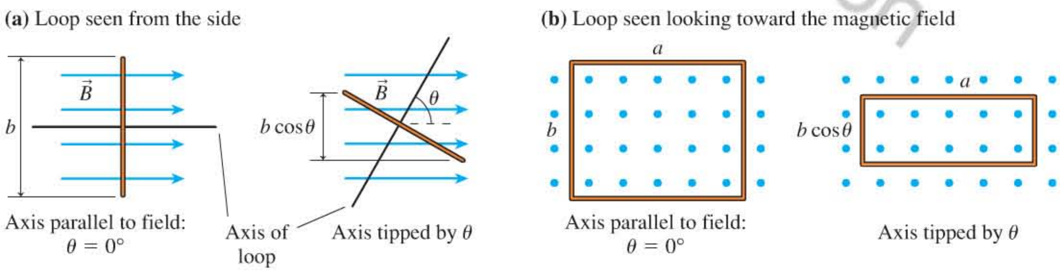
Imagine holding a rectangular loop of wire in front of a fan, as shown in FIGURE 25.8a. The arrows represent the flow of the air. If you want to get the most air through the loop, you know that you should hold the loop perpendicular to the direction of the flow. If you tip the loop from this position, less air will pass through the loop. FIGURE 25.8b is a side view that makes this reduction clear—fewer arrows pass through the tipped loop. Yet another way to visualize this situation is FIGURE 25.8c, which shows a front view with the air coming toward you; the dots represent the front of the arrows. From this point of view it's clear why the flow is smaller: The loop presents a smaller area to the moving air. We say that the *effective area* of the loop has been reduced.

We can apply this idea to a magnetic field passing through a loop. FIGURE 25.9a shows a side view of a loop in a uniform magnetic field. To have the most field vectors going through the loop, we need to turn the loop to be perpendicular to the magnetic field vectors, just as we did for airflow. We define the *axis* of the loop to be a line through the center of the loop that is perpendicular to the plane of the loop. We see that the largest number of field vectors go through the loop when its axis is lined up with the field. Tipping the loop by an angle θ reduces the number of vectors passing through the loop, just for the air from the fan.

FIGURE 25.9b is front view of the loop with the dimensions noted. When the loop is tipped by an angle θ, fewer field vectors pass through the loop because the effective area is smaller. We can define the effective area as

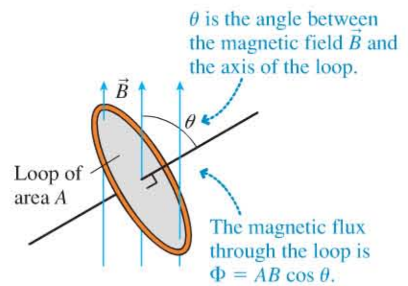
$$A_{\text{eff}} = ab\cos\theta = A\cos\theta \tag{25.8}$$

FIGURE 25.9 The amount of magnetic field passing through a loop depends on the angle.



Ultimately, the amount of field that "goes through" the loop depends on two things: the strength of the field and the effective area of the loop. With this in mind, let's define the **magnetic flux** Φ as

FIGURE 25.10 Definition of magnetic flux.



$$\Phi = A_{\text{eff}}B = AB\cos\theta \tag{25.9}$$

Magnetic flux through area A at angle θ to field B

The magnetic flux measures the amount of magnetic field passing through a loop of area A if the loop is tilted at angle θ from the field. The SI unit of magnetic flux is the **weber.** From Equation 25.9 you can see that

$$1 \text{ weber} = 1 \text{ Wb} = 1 \text{ T}\cdot\text{m}^2$$

The relationship of Equation 25.9 is illustrated in FIGURE 25.10.

EXAMPLE 25.2 Finding the flux of the earth's field through a vertical loop

At a particular location, the earth's magnetic field is 50 μT tipped at an angle of 60° below horizontal. A 10-cm-diameter circular loop of wire sits flat on a table. What is the magnetic flux through the loop?

PREPARE FIGURE 25.11 shows the loop and the field of the earth. The field is tipped by 60°, so the angle of the field with respect to the axis of the loop is $\theta = 30°$. The radius of the loop is 5.0 cm, so the area of the loop is $A = \pi r^2 = \pi(0.050\ \text{m})^2 = 0.0079\ \text{m}^2$.

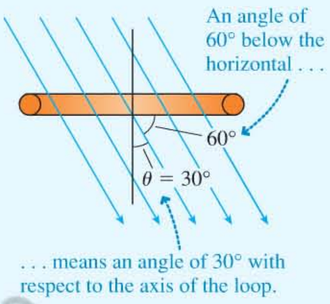


FIGURE 25.11 Finding the flux of the earth's field through a loop.

SOLVE The flux through the loop is given by Equation 25.9, with the angle and area as above:

$$\Phi = AB\cos\theta = (0.0079\ \text{m}^2)(50 \times 10^{-6}\ \text{T})\cos(30°)$$
$$= 3.4 \times 10^{-7}\ \text{Wb}$$

ASSESS It's a small loop and a small field, so a very small flux seems reasonable.

Lenz's Law

Some of the induction experiments from earlier in the chapter could be explained in terms of motional emf, but others had no motion. What they all have in common, though, is that one way or another the magnetic flux through the coil or loop *changes*. We can summarize all of the discoveries as follows: **Current is induced in a loop of wire when the magnetic flux through the loop changes.**

For example, a momentary current is induced in the loop of FIGURE 25.12 as the bar magnet is pushed toward the loop because the flux through the loop increases. Pulling the magnet away from the loop, which decreases the flux, causes the current meter to deflect in the opposite direction. How can we predict the *direction* of the current in the loop?

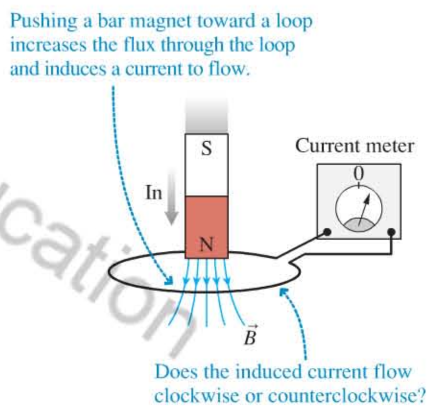


FIGURE 25.12 Pushing a bar magnet toward the loop induces a current in the loop.

The German physicist Heinrich Lenz began to study electromagnetic induction after learning of Faraday's discovery. Lenz developed a rule for determining the direction of the induced current. We now call his rule **Lenz's law,** and it can be stated as follows:

> **Lenz's law** There is an induced current in a closed, conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the *change* in the flux.

Lenz's law is rather subtle, and it takes some practice to see how to apply it.

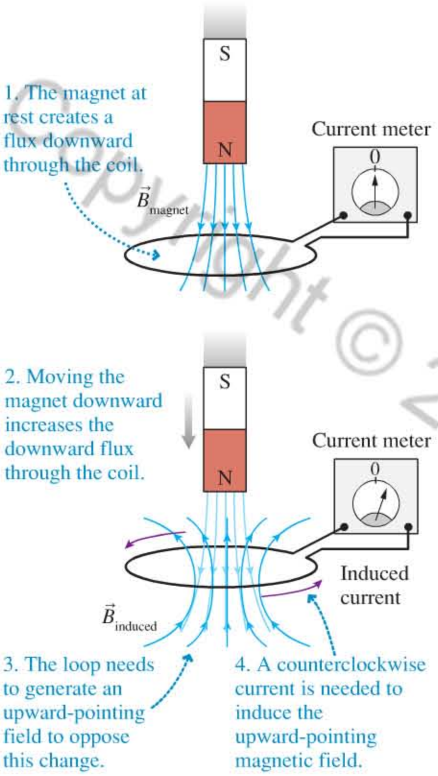
NOTE ► One difficulty with Lenz's law is the term "flux," from a Latin root meaning "flow." In everyday language, the word "flux" may imply that something is changing. Think of the phrase "The situation is in flux." In physics, "flux" simply means "passes through." A steady magnetic field through a loop creates a steady, *un*changing magnetic flux. ◄

Lenz's law tells us to look for situations where the flux is *changing*. This can happen in three ways:

1. The magnetic field through the loop changes (increases or decreases).
2. The loop changes in area or angle.
3. The loop moves into or out of a magnetic field.

We can understand Lenz's law this way: If the flux through a loop changes, a current is induced in a loop. That current generates *its own* magnetic field $\vec{B}_{\text{induced}}$. **It is this induced field that opposes the flux change.** Let's look at an example to clarify what we mean by this statement.

FIGURE 25.13 The induced current is counterclockwise.

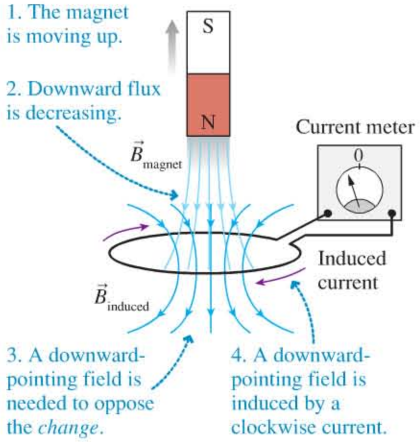


The top part of **FIGURE 25.13** shows a magnet at rest above a coil of wire. The field of the magnet creates a downward flux through the loop. In the lower part of the figure, the magnet is moving toward the loop. This causes the downward magnetic flux through the loop to increase. To oppose this change in flux, which is what Lenz's law requires, the loop itself needs to generate an upward-pointing magnetic field. The induced magnetic field at the center of the loop will point upward if the current is counterclockwise, according to the right-hand rule you learned in Chapter 24. Thus pushing the north end of a bar magnet toward the loop induces a counterclockwise current around the loop. This induced current ceases as soon as the magnet stops moving.

Now suppose the bar magnet is pulled back away from the loop, as shown in **FIGURE 25.14**. There is a downward magnetic flux through the loop, but the flux *decreases* as the magnet moves away. According to Lenz's law, the induced magnetic field of the loop will *oppose this decrease.* To do so, the induced field needs to point in the *downward* direction, as shown in Figure 25.14. Thus as the magnet is withdrawn, the induced current is clockwise, opposite the induced current of Figure 25.13.

NOTE ► Notice that the magnetic field of the bar magnet is pointing downward in both Figures 25.13 and 25.14. It is not the *flux* due to the magnet that the induced current opposes, but the *change* in the flux. This is a subtle but critical distinction. When the field of the magnet points down and is increasing, the induced current opposes the increase by generating an upward field. When the field of the magnet points down but is decreasing, the induced current opposes the decrease by generating a downward field. ◄

FIGURE 25.14 Pulling the magnet away induces a clockwise current.



TACTICS BOX 25.1 Using Lenz's law

MP™

1. Determine the direction of the applied magnetic field. The field must pass through the loop.
2. Determine how the flux is changing. Is it increasing, decreasing, or staying the same?
3. Determine the direction of an induced magnetic field that will oppose the *change* in the flux:
   - Increasing flux: The induced magnetic field points opposite the applied magnetic field.
   - Decreasing flux: The induced magnetic field points in the same direction as the applied magnetic field.
   - Steady flux: There is no induced magnetic field.
4. Determine the direction of the induced current. Use the right-hand rule to determine the current direction in the loop that generates the induced magnetic field you found in step 3.

Exercises 9–12

EXAMPLE 25.3 Applying Lenz's law 1

The switch in the top circuit of **FIGURE 25.15** on the next page has been closed for a long time. What happens in the lower loop when the switch is opened?

PREPARE The current in the upper loop creates a magnetic field. This magnetic field produces a flux through the lower loop. When you open a switch, the current doesn't immediately drop to zero; it falls off over a short time. As the current changes in the upper loop, the flux in the lower loop changes.

SOLVE **FIGURE 25.16** on the next page shows the four steps of using Lenz's law to find the current in the lower loop. Opening the switch induces a counterclockwise current in the lower loop. This is a momentary current, lasting only until the magnetic field of the upper loop drops to zero.

ASSESS The induced current is in the same direction as the original current. This makes sense, because the induced current is opposing the change, a decrease in the current.

FIGURE 25.15 Circuits for Example 25.3.

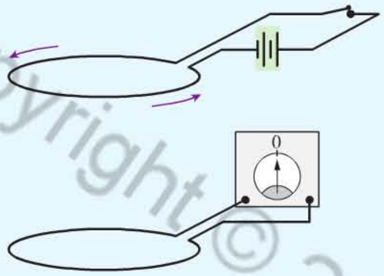
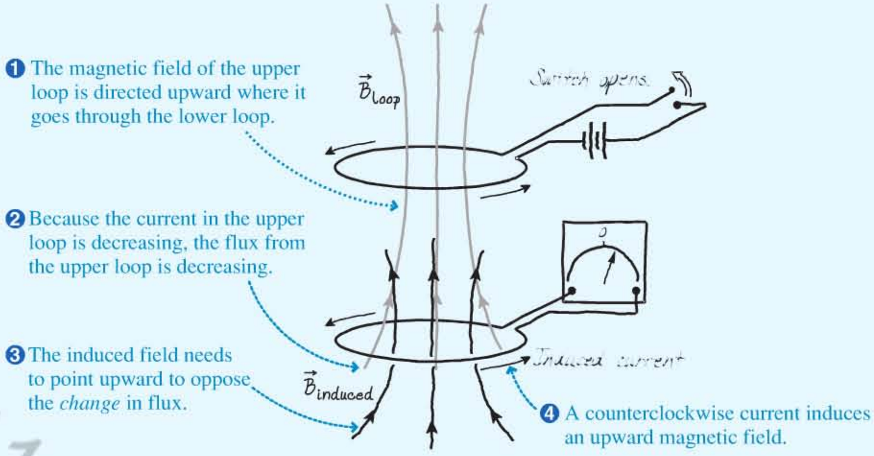


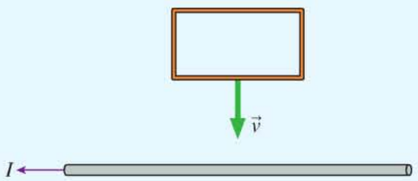
FIGURE 25.16 Finding the induced current.



EXAMPLE 25.4 Applying Lenz's law 2

A loop is moved toward a current-carrying wire as shown in **FIGURE 25.17**. As the wire is moving, is there a clockwise current around the loop, a counterclockwise current, or no current?

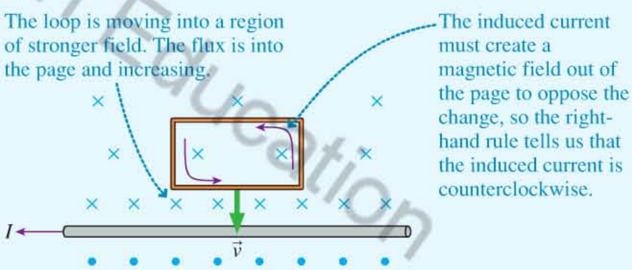
FIGURE 25.17 The moving loop.



PREPARE **FIGURE 25.18** shows that the magnetic field above the wire points into the page. We learned in Chapter 24 that the magnetic field of a straight, current-carrying wire is proportional to $1/r$, where r is the distance away from the wire, so the field is stronger closer to the wire.

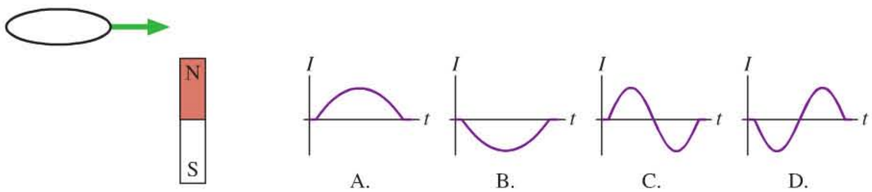
SOLVE As the loop moves toward the wire, the flux through the loop increases. To oppose the *change* in the flux—the increase into the page—the magnetic field of the induced current must point out of the page. Thus, according to the right-hand rule, a counterclockwise current is induced, as shown in Figure 25.18.

FIGURE 25.18 The motion of the loop changes the flux through the loop and induces a current.



ASSESS We could have solved this problem using the concept of motional emf, but treating it as a flux-change problem is more straightforward. The loop moves into a region of stronger field. To oppose the increasing flux, the induced field should be opposite the existing field, so our answer makes sense.

STOP TO THINK 25.2 As a coil moves to the right at constant speed, it passes over the north pole of a magnet and then moves beyond it. Which graph best represents the current in the loop for the time of the motion? A counterclockwise current as viewed from above the loop is a positive current, clockwise is a negative current.



25.4 Faraday's Law

Faraday discovered that a current is induced when the magnetic flux through a conducting loop changes. Lenz's law allows us to find the direction of the induced current. To put electromagnetic induction to practical use, we also need to know the *size* of the induced current.

ActivPhysics Online 13.9–13.10

Keep the (flux) change A credit card has a magnetic strip on the back that has regions of alternating magnetization. "Swiping" the card moves this strip through the circuit of the reader. Different parts of the strip have different fields, so the motion of the strip causes a series of flux changes that induce currents. The pattern of magnetization of the card determines the pattern of the induced currents—and so the card is "read."

In the preceding examples, a change in flux caused a current to flow in a loop of wire. But we know that charges don't start moving spontaneously. A current requires an emf to provide the energy. There *must* be an emf in these circuits, even though the mechanism for this emf is not yet clear.

The emf associated with a changing magnetic flux, regardless of what causes the change, is called an **induced emf** $\mathcal{E}$. If this emf is induced in a complete circuit having resistance R, a current

$$I_{\text{induced}} = \frac{\mathcal{E}}{R} \tag{25.10}$$

is established in the wire as a *consequence* of the induced emf. The direction of the current is given by Lenz's law. The last piece of information we need is the size of the induced emf $\mathcal{E}$.

The research of Faraday and others led to the discovery of the basic law of electromagnetic induction, which we now call **Faraday's law.**

Faraday's law An emf $\mathcal{E}$ is induced in a conducting loop if the magnetic flux through the loop changes. If the flux changes by $\Delta\Phi$ during time interval Δt, the magnitude of the emf is

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right| \tag{25.11}$$

and the direction of the emf is such as to drive an induced current in the direction given by Lenz's law.

In other words, the magnitude of the induced emf is the *rate of change* of the magnetic flux through the loop.

A coil of wire consisting of N turns in a changing magnetic field acts like N batteries in series. The induced emf of each of the coils adds, so the induced emf of the entire coil is

$$\mathcal{E}_{\text{coil}} = N\left|\frac{\Delta\Phi_{\text{per coil}}}{\Delta t}\right| \tag{25.12}$$

Faraday's law allows us to find the *magnitude* of induced emfs and currents; Lenz's law allows us to determine the *direction.*

Using Faraday's Law

Most electromagnetic induction problems can be solved with a three-step strategy.

PROBLEM-SOLVING STRATEGY 25.1 Electromagnetic induction

MP™

PREPARE Make simplifying assumptions about wires and magnetic fields. Draw a picture or a circuit diagram. Use Lenz's law to determine the direction of the induced current.

SOLVE The mathematical representation is based on Faraday's law

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

For an N-turn coil, multiply by N. The size of the induced current is $I = \mathcal{E}/R$.

ASSESS Check that your result has the correct units, is reasonable, and answers the question.

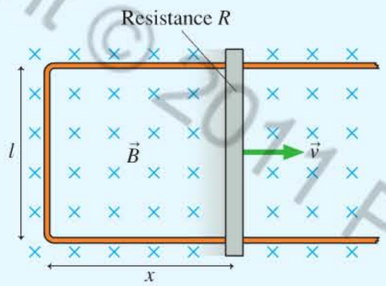
Exercise 15

Let's return to the situation of Figure 25.4, where a wire moves through a magnetic field by sliding on a U-shaped conducting rail. We looked at this problem as an example of motional emf; now, let's look at it using Faraday's law.

EXAMPLE 25.5 Finding the emf using Faraday's law

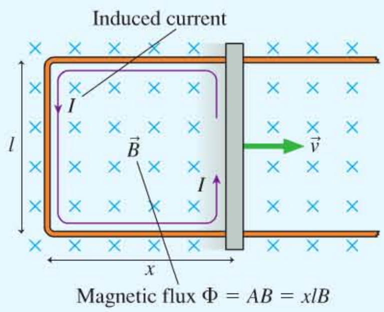
FIGURE 25.19 shows a wire of resistance R sliding on a U-shaped conducting rail. Assume that the conducting rail is an ideal wire. Use Faraday's law and the steps of Problem-Solving Strategy 25.1 to derive an expression for the current in the wire.

FIGURE 25.19 A wire sliding on a rail.



PREPARE **FIGURE 25.20** shows the current loop formed by the wire and the rail. Even though the magnetic field is constant, the flux is changing because the loop is increasing in area. The flux is into the loop and increasing. According to Lenz's law, the induced current must be counterclockwise so as to oppose the change, because the induced magnetic field must be out of the loop.

FIGURE 25.20 Induced current in the sliding wire.



SOLVE The magnetic field $\vec{B}$ is perpendicular to the plane of the loop, so $\theta = 0°$ and the magnetic flux is $\Phi = AB$, where A is the area of the loop. If the sliding wire is distance x from the end, as in Figure 25.20, the area of the loop is $A = xl$ and the flux at that instant of time is

$$\Phi = AB = xlB$$

The flux through the loop increases as the wire moves and x increases. This flux change induces an emf, according to Faraday's law, so we write

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right| = \left|\frac{\Delta(AB)}{\Delta t}\right| = \left|\frac{\Delta(xlB)}{\Delta t}\right|$$

The only quantity in the final ratio that is changing is the position x, so we can write

$$\mathcal{E} = \left|\frac{\Delta(xlB)}{\Delta t}\right| = lB\left|\frac{\Delta x}{\Delta t}\right|$$

But $|\Delta x/\Delta t|$ is the wire's speed v, so the induced emf is

$$\mathcal{E} = vlB$$

The wire and the loop have a total resistance R, thus the magnitude of the induced current is

$$I = \frac{\mathcal{E}}{R} = \frac{vlB}{R}$$

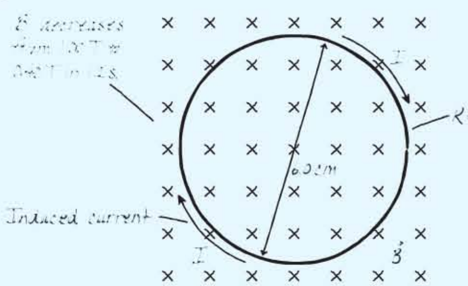
ASSESS This is exactly the same result we found in Section 25.2, where we analyzed this situation by considering the force on moving charge carriers. This is a good check on our work, and a nice connection between the ideas of motional emf and Faraday's law.

EXAMPLE 25.6 Finding the induced current in a circular loop

A patient having an MRI scan has neglected to remove a copper bracelet. The bracelet is 6.0 cm in diameter and has a resistance of 0.010 Ω. The magnetic field in the MRI solenoid is directed along the person's body from head to foot; her bracelet is perpendicular to $\vec{B}$. As a scan is taken, the magnetic field in the solenoid decreases from 1.00 T to 0.40 T in 1.2 s. What are the magnitude and direction of the current induced in the bracelet?

PREPARE We follow the steps in Problem-Solving Strategy 25.1, beginning with a sketch of the situation. **FIGURE 25.21** shows the bracelet and the applied field looking down along the patient's body. The field is directed down through the loop; as the applied field decreases, the flux into the loop decreases. To oppose the decreasing flux, as required by Lenz's law, the field from the induced current must be in the direction of the applied field. Thus, from the right-hand rule, the induced current in the bracelet must be clockwise.

FIGURE 25.21 A circular conducting loop in a decreasing magnetic field.



Continued

SOLVE The magnetic field is perpendicular to the plane of the loop; hence $\theta = 0°$ and the magnetic flux is $\Phi = AB = \pi r^2 B$. The area of the loop doesn't change with time, but B does, so $\Delta\Phi = \Delta(AB) = A\Delta B = \pi r^2\,\Delta B$. The change in the magnetic field during $\Delta t = 1.2$ s is $\Delta B = 0.40\text{ T} - 1.00\text{ T} = -0.60$ T. According to Faraday's law, the magnitude of the induced emf is

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right| = \pi r^2\left|\frac{\Delta B}{\Delta t}\right| = \pi(0.030\text{ m})^2\left|\frac{-0.60\text{ T}}{1.2\text{ s}}\right|$$
$$= \pi(0.030\text{ m})^2(0.50\text{ T/s}) = 0.0014\text{ V}$$

The current induced by this emf is

$$I = \frac{\mathcal{E}}{R} = \frac{0.0014\text{ V}}{0.010\ \Omega} = 0.14\text{ A}$$

The decreasing magnetic field causes a 0.14 A clockwise current during the 1.2 s that the field is decreasing.

ASSESS The emf is quite small, but, because the resistance of the metal bracelet is also very small, the current is respectable. We know that electromagnetic induction produces currents large enough for practical applications, so this result seems plausible. The induced current could easily distort the readings of the MRI machine, and a larger current could cause enough heating to be potentially dangerous. For these and other reasons, operators are careful to have patients remove all metal before an MRI scan.

FIGURE 25.22 Eddy currents.

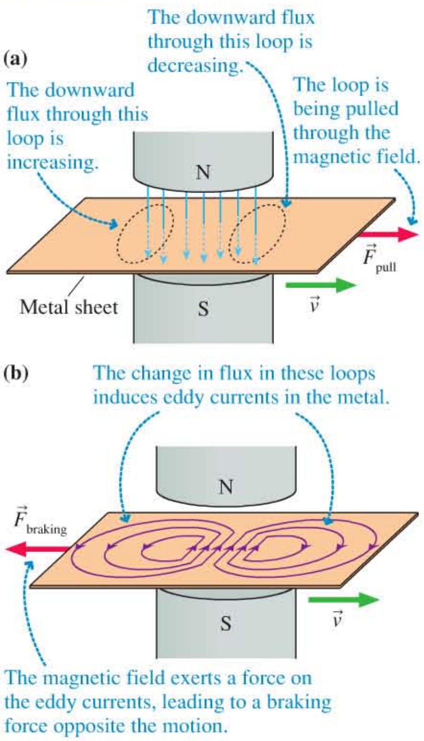
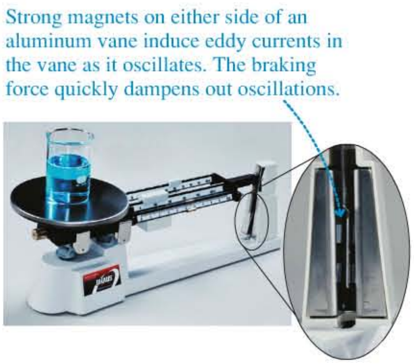


FIGURE 25.23 Eddy-current damping in a balance.



As these two examples show, there are two fundamentally different ways to change the magnetic flux through a conducting loop:

1. The loop can move or expand or rotate, creating a motional emf.
2. The magnetic field can change.

Faraday's law tells us that the induced emf is simply the rate of change of the magnetic flux through the loop, *regardless* of what causes the flux to change. Motional emf is included within Faraday's law as one way of changing the flux, but any other way of changing the flux will have the same result.

Eddy Currents

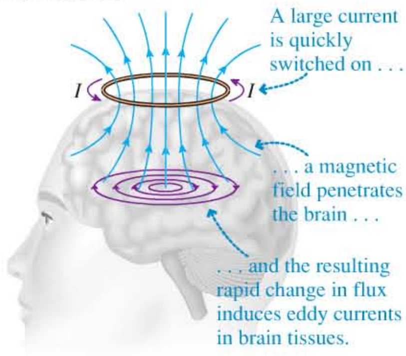
Here is a remarkable physics demonstration that you can try: Take a sheet of copper and place it between the pole tips of a strong magnet, as shown in **FIGURE 25.22a**. Now, pull the copper sheet out of the magnet as fast as you can. Copper is not a magnetic material and thus is not attracted to the magnet, so it comes as quite a surprise to find that it takes a significant effort to pull the metal through the magnetic field.

Let's analyze this situation to discover the origin of the force. Figure 25.22a shows two "loops" lying entirely inside the metal sheet. The loop on the right is leaving the magnetic field, and the flux through it is decreasing. According to Faraday's law, the flux change will induce a current to flow around this loop, just as in a loop of wire, even though this current does not have a wire to define its path. As a consequence, a clockwise—as given by Lenz's law— "whirlpool" of current begins to circulate in the metal, as shown in **FIGURE 25.22b**. Similarly, the loop on the left is entering the field, and the flux through it is increasing. Lenz's law requires this whirlpool of current to circulate the opposite way. These spread-out whirlpools of induced current in a solid conductor are called **eddy currents.**

Figure 25.22b shows the direction of the eddy currents. Notice that both whirlpools are moving in the same direction as they pass through the magnet. The magnet's field exerts a force on this current. By the right-hand rule, this force is to the left, opposite the direction of the pull, and thus it acts as a *braking* force. Because of the braking force, **an external force is required to pull a metal through a magnetic field.** If the pulling force ceases, the magnetic braking force quickly causes the metal to decelerate until it stops. No matter which way the metal is moved, the magnetic forces on the eddy currents act to oppose the motion of the metal. *Magnetic braking* uses the braking force associated with eddy currents to slow trains and transit-system vehicles. It can also provide valuable vibration damping on a much smaller scale, as we see in **FIGURE 25.23**.

Eddy currents can also be induced by changing fields; this has practical applications as well. In a technique known as *transcranial magnetic stimulation* (TMS), a large oscillating magnetic field is applied to the head via a current-carrying coil. **FIGURE 25.24** illustrates how this field produces small eddy currents that stimulate neurons in the tissue of the brain. This produces a short-term inhibitory effect on the neurons in the stimulated region that can produce long-term clinical effects. The technique is also useful in research. By inhibiting the action of specific regions of the brain, researchers can determine the importance of these regions to certain perceptions or tasks.

FIGURE 25.24 Transcranial magnetic stimulation.



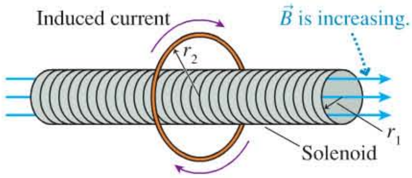
25.5 Induced Fields and Electromagnetic Waves

We will start this section with the puzzle shown in **FIGURE 25.25**. A long, tightly wound solenoid of radius r_1 passes through the center of a conducting loop having a larger radius r_2. The solenoid carries a current and generates a magnetic field. What happens to the loop if the solenoid current changes?

You learned in Chapter 24 that the magnetic field is strong inside a long solenoid but essentially zero outside. Even so, changing the field inside the solenoid causes the flux through the loop to change, so our theory predicts an induced current in the loop. Indeed, you would find an induced current if you did this experiment.

But the loop is completely outside the solenoid, where the magnetic field is zero. How can the charge carriers in the conducting loop possibly "know" that the magnetic field inside the solenoid is changing?

FIGURE 25.25 A changing current in the solenoid induces a current in the loop.



Induced Electric Fields

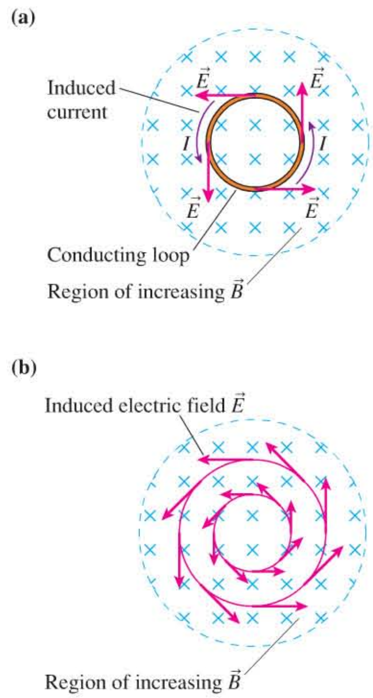
In order to answer this question, we will first consider another related question: When a changing flux through a loop induces a current, what actually *causes* the current? What *force* pushes the charges around the loop against the resistive forces of the metal? When we considered currents in Chapter 22, it was an *electric field* that moved charges through a conductor. Somehow, changing a magnetic field must create an electric field.

In fact, a changing magnetic field *does* cause what we call an **induced electric field.** **FIGURE 25.26a** shows a conducting loop in an increasing magnetic field. According to Lenz's law, there is an induced current in the counterclockwise direction. Something has to act on the charge carriers to make them move, so we can infer that the current is produced by an induced electric field tangent to the loop at all points. The induced electric field is the *mechanism* we were seeking that creates a current when there is a changing magnetic field inside a stationary loop.

But the induced electric field exists whether there is a conducting loop or not. The space in which the magnetic field is changing is filled with the pinwheel pattern of induced electric fields shown in **FIGURE 25.26b**. Charges will move if a conducting path is present, but the induced electric field is there as a direct consequence of the changing magnetic field, whether a conducting path is present or not.

Making this connection between electric and magnetic fields has brought together all of the pieces we have explored so far in this chapter. But there's more to the story of induced fields. Faraday's discovery was the source of inspiration for further investigations that had very far-reaching and practical implications.

FIGURE 25.26 An induced electric field creates a current in the loop.



Maxwell's Theory

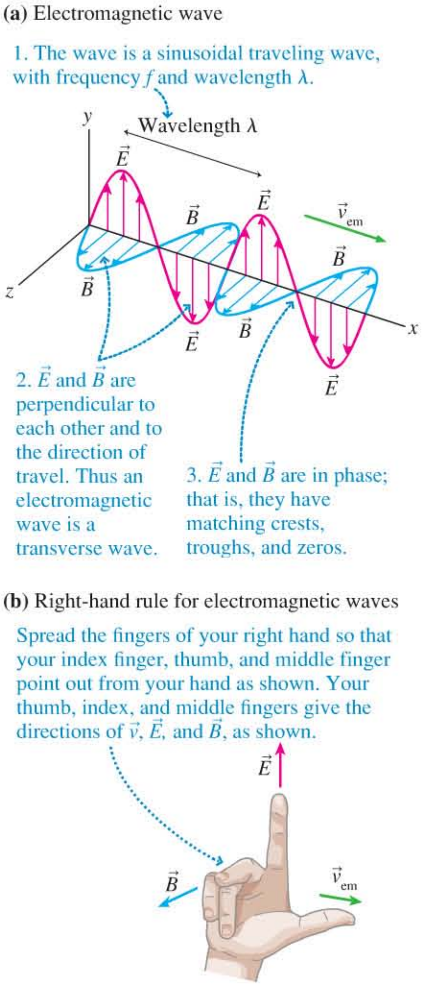
The development of a theory of electricity and magnetism continued with work by the Scottish physicist James Clerk Maxwell, who asked the following question: What about a changing *electric* field? Could this induce a *magnetic* field? Maxwell thought the symmetry was compelling. He proposed that a changing electric field creates an **induced magnetic field.**

◀ **The grandfather of the cell phone** In this photo, Guglielmo Marconi, who is credited with the development of radio communication, or "wireless telegraphy," sits surrounded by high-voltage equipment used in his experiments in the late 1800s. The German scientist Heinrich Hertz discovered that a spark in one circuit emitted a disturbance that affected a second circuit at some distance. Soon after, Marconi developed the technology for producing and detecting these *electromagnetic waves,* transmitting signals, with no wires, over long distances—something we have come to take for granted.

If a changing magnetic field can induce an electric field in the absence of any charges, and a changing electric field can induce a magnetic field in the absence of any currents, Maxwell soon realized that it would be possible to establish self-sustaining electric and magnetic fields independent of any charges or currents. That is, a changing electric field $\vec{E}$ creates a magnetic field $\vec{B}$, which then changes in just the right way to recreate the electric field, which then changes in just the right way to again recreate the magnetic field, with the fields continuously recreated through electromagnetic induction.

Maxwell was able to show that these electric and magnetic fields would be able to sustain themselves, free from charges and currents, if they took the form of an **electromagnetic wave.** The wave would have to have a very specific geometry, shown in FIGURE 25.27a, in which $\vec{E}$ and $\vec{B}$ are perpendicular to each other as well as perpendicular to the direction of travel. FIGURE 25.27b shows a right-hand rule for determining the relative orientations of the fields and the velocity, reminiscent of the right-hand rule for forces from Chapter 24.

FIGURE 25.27 A sinusoidal electromagnetic wave.



Maxwell's theory predicted that an electromagnetic wave would travel with speed

$$v_{em} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \tag{25.13}$$

where ϵ_0 and μ_0 are the permittivity and permeability constants from our expressions for electric and magnetic fields. Maxwell computed that an electromagnetic wave would travel with speed $v_{em} = 3.00 \times 10^8$ m/s.

This is a value you have seen before—it is the speed of light. Making a bold leap of imagination, Maxwell concluded that **light is an electromagnetic wave.** We studied the wave properties of light in Part V, but at that time we were not able to determine just what is "waving." Now we know—light is a wave of electric and magnetic fields.

Maxwell was able to establish the following properties of electromagnetic waves:

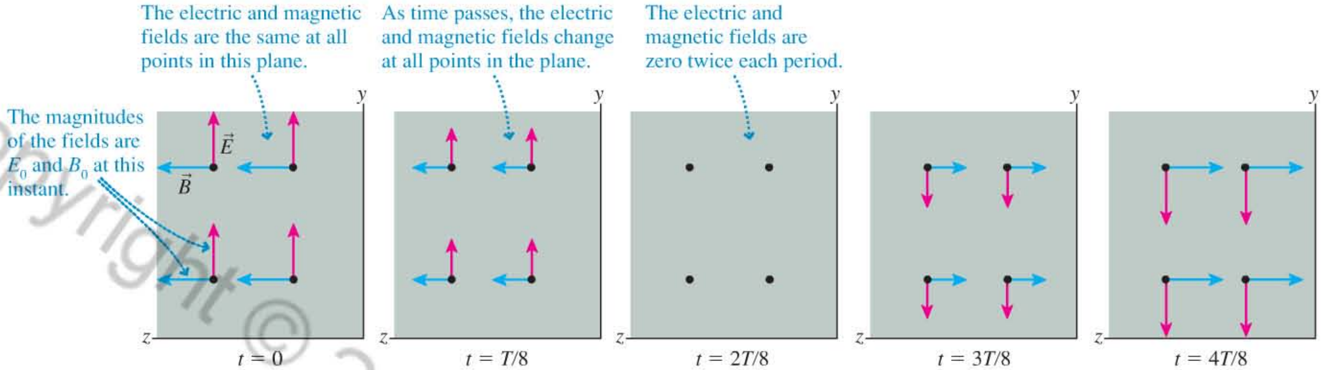
- An electromagnetic wave is a *transverse* wave, as shown in Figure 25.27a.
- Electromagnetic waves can exist at any frequency, not just the frequencies of visible light.
- In a vacuum, all electromagnetic waves travel with the same speed, a speed that we call the *speed of light,* for which we use the symbol c.
- At any point on the wave, the electric and magnetic field strengths are related by $E = cB$.

Figure 25.27a shows the values of the electric and magnetic fields at points along a single line, the x-axis.

NOTE ▶ An $\vec{E}$ vector pointing in the y-direction says that *at that point* on the x-axis, where the vector's tail is, the electric field points in the y-direction and has a certain strength. Nothing is "reaching" to a point in space above the x-axis. ◀

Suppose this electromagnetic wave is a *plane wave* traveling in the x-direction. Recall from Chapter 15 that the displacement of a plane wave is the same at *all points* in any plane perpendicular to the direction of motion. In this case, the fields are the same in any yz-plane. If you were standing on the x-axis as the wave moves toward you, the electric and magnetic fields would vary as in the series of pictures of FIGURE 25.28 on the next page. The $\vec{E}$ and $\vec{B}$ fields at each point in the yz-plane oscillate in time, but they are always synchronized with all the other points in the plane. As the plane wave passed you, you would see a uniform oscillation of the $\vec{E}$ and $\vec{B}$ fields of the wave.

FIGURE 25.28 The fields of an electromagnetic plane wave moving toward you, shown every one-eighth period for half a cycle.



We can adapt our equation for traveling waves from Chapter 15 to electromagnetic waves. If a plane electromagnetic wave moves in the x-direction with the electric field along the y-axis, then the magnetic field is along the z-axis. The equations for the electric and magnetic fields of a wave with wavelength λ and period T are

$$E_y = E_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right) \qquad B_z = B_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right) \qquad (25.14)$$

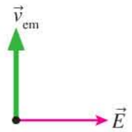
E_0 and B_0 are the amplitudes of the oscillating fields. The amplitudes of the fields must have a particular relationship:

$$E_0 = cB_0 \qquad (25.15)$$

Relationship between field amplitudes for an electromagnetic wave

STOP TO THINK 25.3 An electromagnetic wave is traveling in the direction shown. What is the direction of the magnetic field at this instant?

A. Toward the top of the page
B. Toward the bottom of the page
C. To the left
D. To the right
E. Into the page
F. Out of the page



25.6 Properties of Electromagnetic Waves

Electromagnetic waves are oscillations of the electric and magnetic field, but they are still waves, and all the general principles we have learned about waves apply.

In Chapter 15, we learned that we could characterize sinusoidal waves by their speed, wavelength, and frequency, with these related by the fundamental relationship $v = \lambda f$. All electromagnetic waves move at the speed of light, $v_{em} = c$, so this relationship becomes

$$c = \lambda f \qquad (25.16)$$

The *spectrum* of electromagnetic waves ranges from waves of long wavelength and (relatively) low frequency (radio waves and microwaves) to waves of short wavelength and high frequency (visible light, ultraviolet, and x rays), as we saw in Chapter 15. Later in the chapter we will explore the properties of different parts of the electromagnetic spectrum. For now, we will concentrate on physical properties that all electromagnetic waves share.

Energy of Electromagnetic Waves

All waves transfer energy. Ocean waves erode beaches, sound waves set your eardrum to vibrating, and light from the sun warms the earth. In all of these cases, the waves carry energy from the point where they are emitted to another point where

A field-fired furnace The energy from the sun is carried through space by electromagnetic waves—that is, it is carried by electric and magnetic fields. The mirrors of this solar furnace in the Pyrenees in southern France concentrate the electromagnetic waves from the sun to an intensity 1000 times that of normal sunlight, allowing researchers to test the high-temperature properties of materials at up to 3800°C.

their energy is transferred to an object. In water waves, the wave energy is the kinetic and gravitational potential energy of water; for electromagnetic waves, the wave energy is in the form of electric and magnetic fields. The energy of the wave depends on the amplitudes of these fields. If the electric and magnetic fields have greater amplitudes, the wave will carry more energy.

In our earlier study of waves, we defined the *intensity* of a wave (measured in W/m^2) to be $I = P/A$, where P is the power (energy transferred per second) of a wave that impinges on area A. The intensity of an electromagnetic wave depends on the amplitudes of the oscillating electric and magnetic fields:

$$I = \frac{P}{A} = \frac{1}{2}c\epsilon_0 E_0^2 = \frac{1}{2}\frac{c}{\mu_0}B_0^2 \qquad (25.17)$$

Intensity of an electromagnetic wave with field amplitudes E_0 and B_0

The intensity of a plane wave, such as that of a laser beam, does not change with distance. As we saw in Chapter 15, the intensity of a spherical wave, spreading out from a point, must decrease with the square of the distance to conserve energy. If a source with power P_{source} emits waves *uniformly* in all directions, the wave intensity at distance r is

$$I = \frac{P_{\text{source}}}{4\pi r^2} \qquad (25.18)$$

The intensities of the electromagnetic waves from antennas, cell phones, and other "point sources" are reasonably well described by Equation 25.18.

EXAMPLE 25.7 Electric and magnetic fields of a cell phone

A digital cell phone emits 0.60 W of 1.9 GHz radio waves. What are the amplitudes of the electric and magnetic fields at a distance of 10 cm?

PREPARE We can approximate the cell phone as a point source of waves, so we can use Equation 25.18 to determine the intensity of the waves at the noted distance. Once we know the intensity, we can compute the field amplitudes.

SOLVE The intensity at a distance of 10 cm is

$$I = \frac{P_{\text{source}}}{4\pi r^2} = \frac{0.60\text{ W}}{4\pi(0.10\text{ m})^2} = 4.8\text{ W/m}^2$$

We can rearrange Equation 25.17 to solve for the amplitude of the electric field:

$$E_0 = \sqrt{\frac{2I}{c\varepsilon_0}} = \sqrt{\frac{2(4.8\text{ W/m}^2)}{(3.0\times10^8\text{ m/s})(8.85\times10^{-12}\text{ C}^2/\text{N}\cdot\text{m}^2)}} = 60\text{ V/m}$$

We can then use Equation 25.15, which relates the amplitudes of the electric and magnetic fields for an electromagnetic wave, to find the amplitude of the magnetic field:

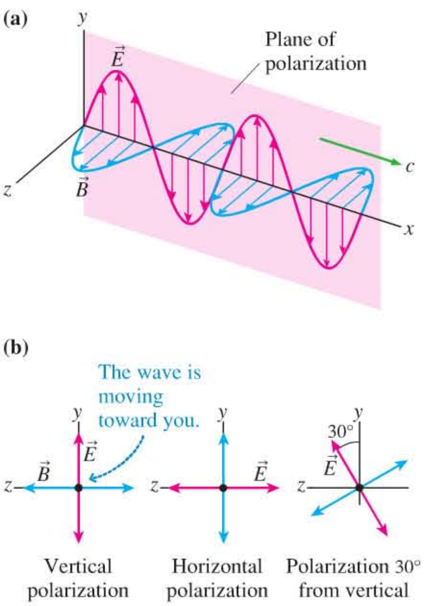
$$B_0 = \frac{E_0}{c} = 2.0\times10^{-7}\text{ T}$$

ASSESS The electric field amplitude is reasonably small. For comparison, the typical electric field due to atmospheric electricity is 100 V/m; the field near a charged Van de Graaf generator can be 1000 times larger than this. This seems reasonable; we know that the electric fields near a cell phone's antenna aren't large enough to produce significant effects. The magnetic field is smaller yet, only 1/250th of the earth's field, which, as you know, is quite weak. The interaction of electromagnetic waves with matter is mostly due to the electric field; the magnetic field is generally small enough that we can ignore its effects.

Polarization

The electric field vectors of an electromagnetic wave lie in a plane perpendicular to the direction of propagation. The plane containing the electric field vectors is called the **plane of polarization.** In FIGURE 25.29a, the wave is traveling along the x-axis, and the plane of polarization is the xy-plane. If the wave were moving toward you, it

FIGURE 25.29 The polarization of an electromagnetic wave is determined by the plane in which the electric field oscillates.



would appear as in the first diagram in **FIGURE 25.29b**. This particular wave is *vertically polarized* ($\vec{E}$ oscillating along the y-axis). The second diagram of Figure 25.29b shows a wave that is *horizontally polarized* ($\vec{E}$ oscillating along the z-axis). The plane of polarization needn't be horizontal or vertical; it can have any orientation, as in the third diagram.

ActivPhysics 16.9

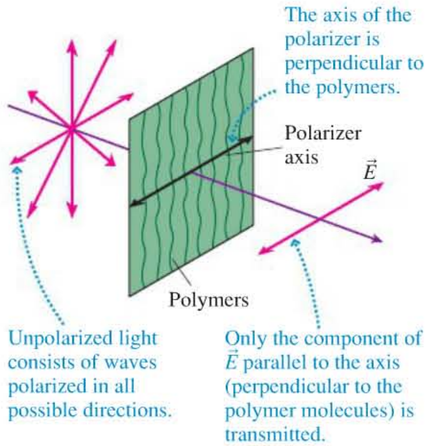
NOTE ► This use of the term "polarization" is completely independent of the idea of *charge polarization* that you learned about in Chapter 20. ◄

Most natural sources of electromagnetic radiation are *unpolarized.* Each atom in the sun's hot atmosphere emits light independently of all the other atoms, as does each tiny piece of metal in the incandescent filament of a lightbulb. An electromagnetic wave that you see or measure is a superposition of waves from each of these tiny emitters. Although the wave from each individual emitter is polarized, it is polarized in a random direction with respect to the waves from all its neighbors. The resulting wave, a superposition of waves with electric fields in all possible directions, is *unpolarized*.

We can create polarized light by sending unpolarized light through a *polarizing filter.* A typical polarizing filter is a plastic sheet containing long organic molecules called polymers, as shown in **FIGURE 25.30**. The molecules are aligned to form a grid, like the metal bars in a barbecue grill, then treated so they conduct electrons along their length.

As a light wave travels through a polarizing filter, the component of the electric field oscillating parallel to the polymer grid drives the electrons up and down the molecules. The electrons absorb energy from the light wave, so the parallel component of $\vec{E}$ is absorbed in the filter. But the conduction electrons can't oscillate perpendicular to the molecules, so the component of $\vec{E}$ perpendicular to the polymer grid passes through without absorption. Thus the light wave emerging from a polarizing filter is polarized perpendicular to the polymer grid. We call the direction of the transmitted polarization the axis of the polarizer.

FIGURE 25.30 A polarizing filter.



Suppose a *polarized* light wave with electric field amplitude E_{incident} approaches a polarizing filter with a vertical axis (that is, the filter transmits only vertically polarized light). What is the intensity of the light that passes through the filter? **FIGURE 25.31** shows that the oscillating electric field of the polarized light can be decomposed into horizontal and vertical components. The vertical component will pass; the horizontal component will be blocked. As we see in Figure 25.31, the magnitude of electric field of the light transmitted by the filter is

$$E_{\text{transmitted}} = E_{\text{incident}} \cos\theta \tag{25.19}$$

Because the intensity depends on the square of the electric field amplitude, the transmitted intensity is related to the incident intensity by what is known as **Malus's law:**

$$I_{\text{transmitted}} = I_{\text{incident}}(\cos\theta)^2 \tag{25.20}$$

Malus's law for transmission of polarized light by a polarizing filter

FIGURE 25.31 An incident electric field can be decomposed into components parallel and perpendicular to a polarizer's axis.

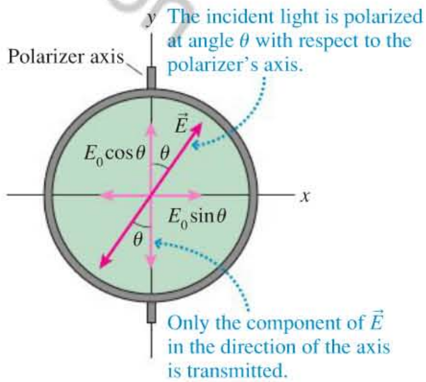


FIGURE 25.32 shows how Malus's law can be demonstrated with two polarizing filters. The first, called the *polarizer,* is used to produce polarized light of intensity I_0.

FIGURE 25.32 The intensity of the transmitted light depends on the angle between the polarizing filters.

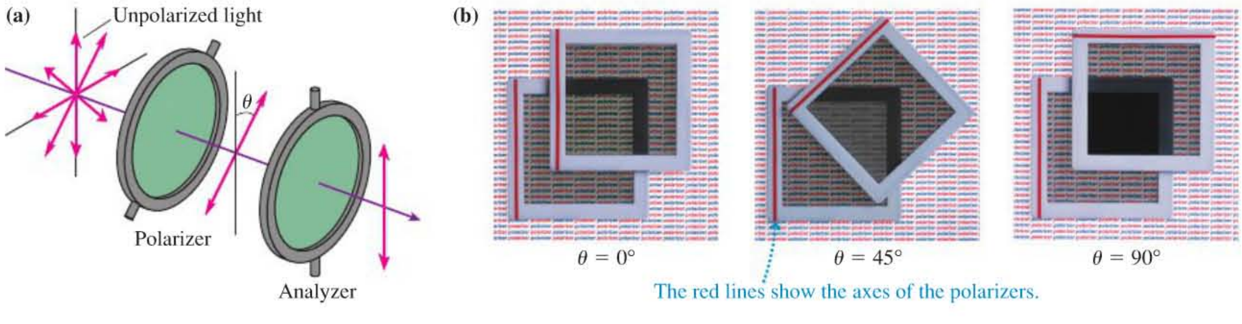


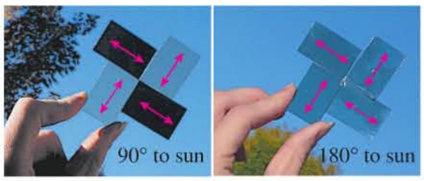
FIGURE 25.33 Polarized light micrograph of a thin section of molar teeth.

The second, called the *analyzer,* is rotated by angle θ relative to the polarizer. As the photographs of Figure 25.32b show, the transmission of the analyzer is (ideally) 100% when $\theta = 0°$ and steadily decreases to zero when $\theta = 90°$. Two polarizing filters with perpendicular axes, called *crossed polarizers,* block all the light.

Suppose you place an object between two crossed polarizers. Normally, no light would make it through the analyzer, and the object would appear black. But if the object is able to *change* the polarization of the light, some of the light emerging from the object will be able to pass through the analyzer. This can be a valuable analytical technique. Many minerals, crystals, and biological molecules do, indeed, change the polarization of light. As an example, FIGURE 25.33 shows a micrograph of a very thin section of molar teeth as it appears when viewed between crossed polarizers. Different minerals and different materials in the teeth affect the polarization of the light in different ways. The result is an image that clearly highlights the different tissues in the teeth.

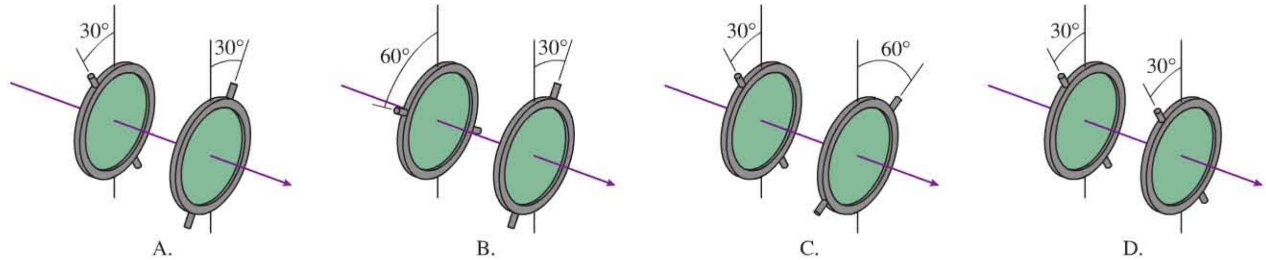
In polarizing sunglasses, the polarization axis is vertical (when the glasses are in the normal orientation) so that the glasses transmit only vertically polarized light. *Glare*—the reflection of the sun and the skylight from lakes and other horizontal surfaces—has a strong horizontal polarization. This light is almost completely blocked, so the sunglasses "cut glare" without affecting the main scene you wish to see.

The molecules in a polarizing filter absorb light if its electric field is oriented along the axis of the molecules. Light-sensing *photopigments* in the eye are also long-chain molecules with similar properties; they are much more likely to absorb and respond to light that is polarized along the axis of the molecules. In human eyes, the orientation of the photopigments is random, so we do not have a polarization sense. But honeybees and other insects have light-sensing cells in their eyes in which the axes of the photopigment molecules are aligned. The response of these cells varies with the polarization of the light. Bees and other insects use this polarization sense to navigate, as shown in the photo below.



◀ **Making a beeline** BIO At an angle of 90° to the sun, skylight is partially polarized because of scattering from air molecules. In the left photo, this polarization causes different transmission through polarizers with different axes. Opposite the sun in the sky, the skylight is unpolarized, causing equal transmission for all of the polarizers in the right photo. We can't sense this sky polarization without external filters, but honeybees can. Light-sensing cells in honeybee eyes have different polarization axes, so they sense the polarization of the sky in a similar fashion to the photos. A bee can determine the sun's position from a tiny patch of clear sky, so bees can reliably navigate even in dense forest cover.

STOP TO THINK 25.4 Unpolarized light of equal intensity is incident on four pairs of polarizing filters. Rank in order, from largest to smallest, the intensities I_A to I_D transmitted through the second polarizer of each pair.



25.7 The Photon Model of Electromagnetic Waves

FIGURE 25.34 shows three photographs made with a camera in which the film has been replaced by a special high-sensitivity detector. A correct exposure, at the bottom, shows a perfectly normal photograph of a woman. But with very faint illumination (top), the picture is *not* just a dim version of the properly exposed photo. Instead, it is a collection of dots. A few points on the detector have registered the presence of light, but most have not. As the illumination increases, the density of these dots increases until the dots form a full picture.

This is not what we might expect. If light is a wave, reducing its intensity should cause the picture to grow dimmer and dimmer until it disappears, but the entire picture would remain present. It should be like turning down the volume on your stereo until you can no longer hear the sound. Instead, the top photograph in Figure 25.34 looks as if someone randomly threw "pieces" of light at the detector, causing full exposure at some points but no exposure at others.

If we did not know that light is a wave, we would interpret the results of this experiment as evidence that light is a stream of some type of particle-like object. If these particles arrive frequently enough, they overwhelm the detector and it senses a steady "river" instead of the individual particles in the stream. Only at very low intensities do we become aware of the individual particles.

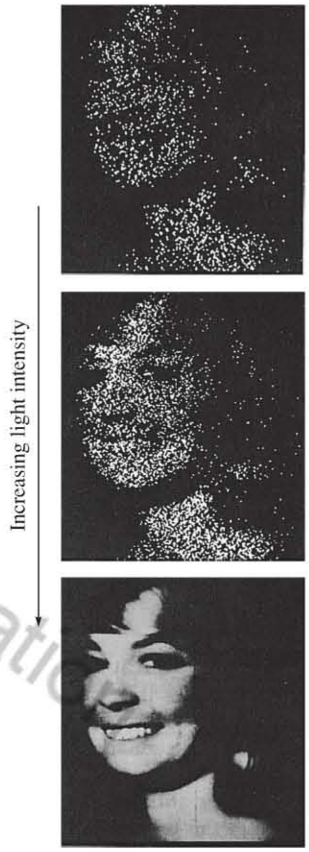
As we will see in Chapter 28, many experiments convincingly lead to the surprising result that **electromagnetic waves, although they are waves, have a particle-like nature.** These particle-like components of electromagnetic waves are called **photons.**

The **photon model** of electromagnetic waves consists of three basic postulates:

1. Electromagnetic waves consist of discrete, massless units called photons. A photon travels in vacuum at the speed of light, 3.00×10^8 m/s.
2. Each photon has energy
$$E_{\text{photon}} = hf \tag{25.21}$$
where f is the frequency of the wave and h is a *universal constant* called **Planck's constant.** The value of Planck's constant is
$$h = 6.63 \times 10^{-34}\ \text{J}\cdot\text{s}$$
In other words, the electromagnetic waves come in discrete "chunks" of energy hf. The higher the frequency, the more energetic the chunks.
3. The superposition of a sufficiently large number of photons has the characteristics of a continuous electromagnetic wave.

FIGURE 25.34 Photographs made with an increasing level of light intensity.

The photo at very low light levels shows individual points, as if particles are arriving at the detector.



The particle-like behavior is not noticeable at higher light levels.

EXAMPLE 25.8 Finding the energy of a photon of visible light

550 nm is the approximate average wavelength of visible light.

a. What is the energy of a photon with a wavelength of 550 nm?
b. A 40 W incandescent lightbulb emits about 1 J of visible light energy every second. Estimate the number of visible light photons emitted per second.

SOLVE a. The frequency of the photon is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8\ \text{m/s}}{550 \times 10^{-9}\ \text{m}} = 5.4 \times 10^{14}\ \text{Hz}$$

Equation 25.21 gives us the energy of this photon:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34}\ \text{J}\cdot\text{s})(5.4 \times 10^{14}\ \text{Hz}) = 3.6 \times 10^{-19}\ \text{J}$$

Continued

This is an extremely small energy! In fact, photon energies are so small that they are usually measured in electron volts (eV) rather than joules. Recall that $1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$. With this, we find that the photon energy is

$$E_{\text{photon}} = 3.6 \times 10^{-19}\ \text{J} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \text{J}} = 2.3\ \text{eV}$$

b. The photons emitted by a lightbulb span a range of energies, because the light spans a range of wavelengths, but the *average* photon energy corresponds to a wavelength near 550 nm. Thus we can estimate the number of photons in 1 J of light as

$$N \approx \frac{1\ \text{J}}{3.6 \times 10^{-19}\ \text{J/photon}} \approx 3 \times 10^{18}\ \text{photons}$$

A typical lightbulb emits about 3×10^{18} photons every second.

ASSESS The number of photons emitted per second is staggeringly large. It's not surprising that in our everyday life we sense only the river and not the individual particles within the flow.

TABLE 25.1 Energies of some atomic and molecular processes

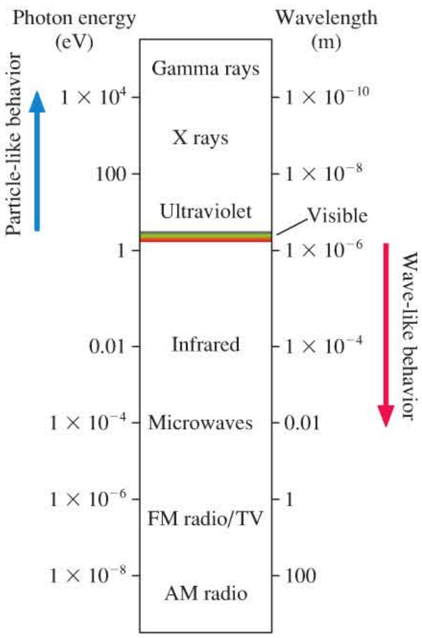
Process	Energy
Breaking a hydrogen bond between two water molecules	0.24 eV
Energy released in metabolizing one molecule of ATP	0.32 eV
Breaking the bond between atoms in a water molecule	4.7 eV
Ionizing a hydrogen atom	13.6 eV

As we saw, a single photon of light at a wavelength of 550 nm has an energy of 2.3 eV. It is worthwhile to see just what 2.3 eV "buys" in interactions with atoms and molecules. Table 25.1 shows some energies required for typical atomic and molecular processes. These values show that 2.3 eV is a significant amount of energy on an atomic scale. It is certainly enough to cause a molecular transformation (as it does in the sensory system of your eye), and photons with a bit more energy (shorter wavelength) can break a covalent bond. The photon model of light will be essential as we explore the interaction of electromagnetic waves with matter.

STOP TO THINK 25.5 Two FM radio stations emit radio waves at frequencies of 90.5 MHz and 107.9 MHz. Each station emits the same total power. If you think of the radio waves as photons, which station emits the larger number of photons per second?

A. The 90.5 MHz station.
B. The 107.9 MHz station.
C. Both stations emit the same number of photons per second.

FIGURE 25.35 The electromagnetic spectrum.



25.8 The Electromagnetic Spectrum

We have now seen two very different ways to look at electromagnetic waves: as oscillating waves of the electric and magnetic fields, and as particle-like units of the electromagnetic field called photons. This dual nature of electromagnetic waves is something we will discuss at length in Chapter 28. For now, we will note that each view is appropriate in certain circumstances. For example, we speak of radio *waves* but of x *rays*. The "ray" terminology tells us that x rays are generally better described as photons than as waves.

FIGURE 25.35 shows the *electromagnetic spectrum* with photon energy (in eV) and wavelength (in m) scales. As you can see, electromagnetic waves span an extraordinarily wide range of wavelengths and energies. Radio waves have wavelengths of many meters but very low photon energies—only a few billionths of an eV. Because the photon energies are so small, radio waves are well described by Maxwell's theory of electromagnetic waves. At the other end of the spectrum, x rays and gamma rays have very short wavelengths and very high photon energies—large enough to ionize atoms and break molecular bonds. Consequently, x rays and gamma rays, although they do have wave-like characteristics, are best described as photons. Visible light is in the middle. As we will see in Chapter 28, we must consider *both* views to fully understand the nature of visible light.

Radio Waves and Microwaves

An electromagnetic wave is self-sustaining, independent of charges or currents. However, charges and currents are needed at the *source* of an electromagnetic wave. Radio waves and microwaves are generally produced by the motion of charged particles in an antenna.

FIGURE 25.36 reminds you what the electric field of an electric dipole looks like. If the dipole is vertical, the electric field $\vec{E}$ at points along the horizontal axis in the figure is also vertical. Reversing the dipole, by switching the charges, reverses $\vec{E}$. If the charges were to *oscillate* back and forth, switching position at frequency f, then $\vec{E}$ would oscillate in a vertical plane. The changing $\vec{E}$ would then create an induced magnetic field $\vec{B}$, which could then create an $\vec{E}$, which could then create a $\vec{B}$, . . . , and a vertically polarized electromagnetic wave at frequency f would radiate out into space.

This is exactly what an **antenna** does. **FIGURE 25.37** shows two metal wires attached to the terminals of an oscillating voltage source. The figure shows an instant when the top wire is negative and the bottom is positive, but these will reverse in half a cycle. The wire is basically an oscillating dipole, and it creates an oscillating electric field. The oscillating $\vec{E}$ induces an oscillating $\vec{B}$, and they take off as an electromagnetic wave at speed $v_{em} = c$. The wave does need oscillating charges as a *wave source,* but once created it is self-sustaining and independent of the source.

Radio waves are *detected* by antennas as well. The electric field of a vertically polarized radio wave drives a current up and down a vertical conductor, producing a potential difference that can be amplified. For best reception, the antenna length should be about $\frac{1}{4}$ of a wavelength. A typical cell phone works at 1.9 GHz, with wavelength $\lambda = c/f = 16$ cm. Thus a cell phone antenna should be about 4 cm long, or about $1\frac{1}{2}$ inches. The antenna on your cell phone may seem quite short, but it is the right length to do its job.

AM radio has a lower frequency and thus a longer wavelength—typically 300 m. Having an antenna that is $\frac{1}{4}$ of a wavelength—75 m long!—is simply not practical. Instead, the antenna in an AM radio consists of a coil of wire wrapped around a core of magnetic material. This antenna detects the *magnetic* field of the radio wave. The changing flux of the wave's magnetic field induces an emf in the coil that is detected and amplified by the receiver.

FIGURE 25.36 The electric field of an oscillating dipole.

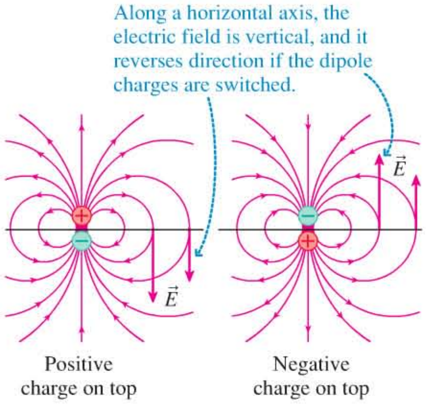
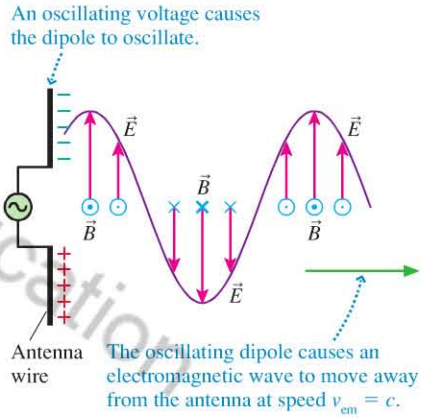


FIGURE 25.37 An antenna generates a self-sustaining electromagnetic wave.

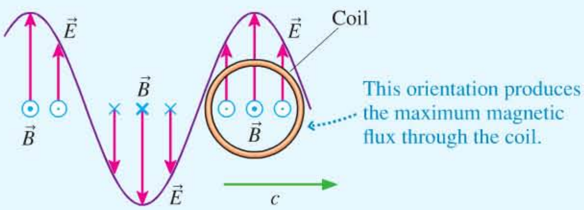


CONCEPTUAL EXAMPLE 25.9 **Orienting a coil antenna**

A vertically polarized AM radio wave is traveling to the right. How should you orient a coil antenna to detect the oscillating magnetic field component of the wave?

REASON You want the oscillating magnetic field of the wave to produce the maximum possible induced emf in the coil, which requires the maximum changing flux. The flux is maximum when the coil is perpendicular to the magnetic field of the electromagnetic wave, as in **FIGURE 25.38**. Thus the plane of the coil should match the wave's plane of polarization.

FIGURE 25.38 A coil antenna.

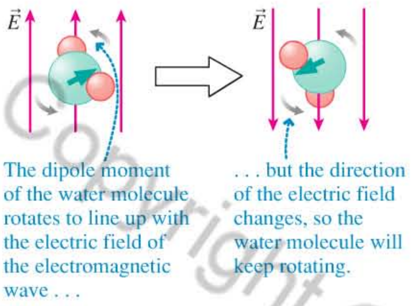


ASSESS Coil antennas are highly directional. If you turn an AM radio—and thus the antenna—in certain directions, you will no longer have the correct orientation of the magnetic field and the coil, and reception will be poor.

TRY IT YOURSELF

Unwanted transmissions Airplane passengers are asked to turn off all portable electronic devices during takeoff and landing. To see why, hold an AM radio near your computer and adjust the tuning as the computer performs basic operations, such as opening files. You will pick up intense static because the rapid switching of voltages in circuits causes computers—and other electronic devices—to emit radio waves, whether they're designed for communications or not. These electromagnetic waves could interfere with the airplane's electronics.

FIGURE 25.39 A radio wave interacts with matter.



In materials with no free charges, the electric fields of radio waves and microwaves can interact with matter by exerting a torque on molecules, such as water, that have a permanent electric dipole moment, as shown in FIGURE 25.39. The molecules acquire kinetic energy from the wave; then their collisions with other molecules transform that energy into thermal energy, increasing the temperature.

This is how a microwave oven heats food. Water molecules, with their large dipole moment, rotate in response to the electric field of the microwaves, then transfer this energy to the food via molecular collisions.

Infrared, Visible Light, and Ultraviolet

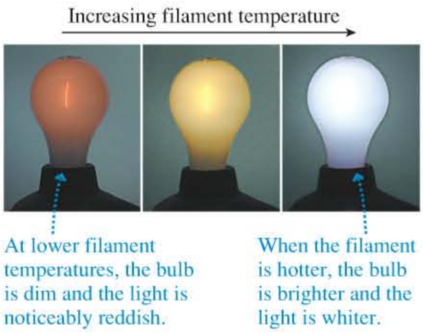
Radio waves can be produced by oscillating charges in an antenna. At the higher frequencies of infrared, visible light, and ultraviolet, the "antennas" are individual atoms. This portion of the electromagnetic spectrum is *atomic radiation.*

Nearly all the atomic radiation in our environment is *thermal radiation* due to the thermal motion of the atoms in an object. As we saw in Chapter 12, thermal radiation—a form of heat transfer—is described by Stefan's law: If heat energy Q is radiated in a time interval Δt by an object with surface area A and absolute temperature T, the *rate* of heat transfer $Q/\Delta t$ (joules per second) is

$$\frac{Q}{\Delta t} = e\sigma A T^4 \tag{25.22}$$

The constant e in this equation is the object's emissivity, a measure of its effectiveness at emitting electromagnetic waves, and σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2 \cdot K^4)}$.

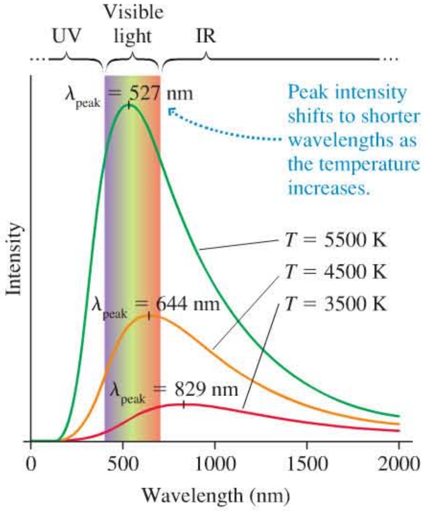
FIGURE 25.40 The brightness of the bulb varies with the temperature of the filament.



In Chapter 12 we considered the amount of energy radiated and its dependence on temperature. The filament of an incandescent bulb glows simply because it is hot. If you increase the current through a lightbulb filament, the filament temperature increases and so does the total energy emitted by the bulb, in accordance with Stefan's law. The three pictures in FIGURE 25.40 show a glowing lightbulb with the filament at successively higher temperatures. We can clearly see an increase in brightness in the sequence of three photographs.

But it's not just the brightness that varies. The *color* of the emitted radiation changes as well. At low temperatures, the light from the bulb is quite red. (A dim bulb doesn't look this red to your eye because your brain, knowing that the light "should" be white, compensates. But the camera doesn't lie.) Looking at the change in color as the temperature of the bulb rises in Figure 25.40, we see that **the spectrum of thermal radiation changes with temperature.**

FIGURE 25.41 A thermal emission spectrum depends on the temperature.

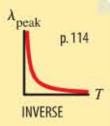


If we measure the intensity of thermal radiation as a function of wavelength for an object at three temperatures, 3500 K, 4500 K, and 5500 K, the data appear as in FIGURE 25.41. Notice two important features:

- Increasing the temperature increases the intensity at all wavelengths. **Making the object hotter causes it to emit more radiation across the entire spectrum.**
- Increasing the temperature causes the peak intensity to shift to a shorter wavelength. **The higher the temperature, the shorter the wavelength of the peak of the spectrum.**

It is this variation of the peak wavelength that causes the change in color of the glowing filament in Figure 25.40. The temperature dependence of the peak wavelength of thermal radiation is known as *Wien's law,* which appears as follows:

$$\lambda_{peak}(\text{in nm}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{T(\text{in K})} \tag{25.23}$$



Wien's law for the peak wavelength of a thermal emission spectrum

EXAMPLE 25.10 Finding peak wavelengths

What are the wavelengths of peak intensity and the corresponding spectral regions for radiating objects at (a) normal human body temperature of 37°C, (b) the temperature of the filament in an incandescent lamp, 1500°C, and (c) the temperature of the surface of the sun, 5800 K?

PREPARE All of the objects emit thermal radiation, so the peak wavelengths are given by Equation 25.23.

SOLVE First, we convert temperatures to kelvin. The temperature of the human body is $T = 37 + 273 = 310$ K, and the filament temperature is $T = 1500 + 273 = 1773$ K. Equation 25.23 then gives the wavelengths of peak intensity as

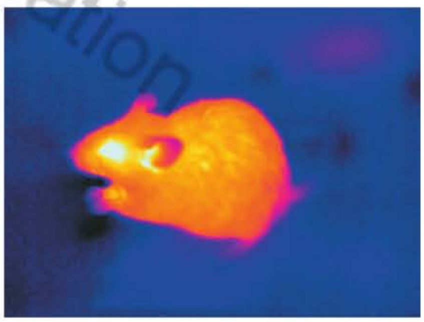
a. $\lambda_{peak}(\text{body}) = \dfrac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{310 \text{ K}} = 9.4 \times 10^3 \text{ nm} = 9.4\ \mu\text{m}$

b. $\lambda_{peak}(\text{filament}) = \dfrac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{1773 \text{ K}} = 1600 \text{ nm}$

c. $\lambda_{peak}(\text{sun}) = \dfrac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{5800 \text{ K}} = 500 \text{ nm}$

ASSESS The peak of the emission curve at body temperature is far into the infrared region of the spectrum, well below the range of sensitivity of human vision. You don't see someone "glow," although people do indeed emit significant energy in the form of electromagnetic waves, as we saw in Chapter 12. The sun's emission peaks right in the middle of the visible spectrum, which seems reasonable. Interestingly, most of the energy radiated by an incandescent bulb is *not* visible light. The tail of the emission curve extends into the visible region, but the peak of the emission curve—and most of the emitted energy—is in the infrared region of the spectrum. A 100 W bulb emits only a few watts of visible light.

▶ It's the pits . . . BIO Certain snakes—including rattlesnakes and other *pit vipers*—can hunt in total darkness. Prey animals are warm, and warm objects emit thermal radiation. In the top photo, notice the pits in front of the viper's eyes. These pits are actually a second set of vision organs; they have sensitive tissue at the bottom that allow them to sense this thermal radiation. The pits are sensitive to infrared wavelengths of $\approx 10\ \mu$m, near the wavelength of peak emission at mammalian body temperatures. Pit vipers sense the electromagnetic waves *emitted* by warm-blooded animals, such as the thermal radiation emitted by the mouse, shown in the lower image. They need no light to "see" you. You emit a "glow" they can detect.



Infrared radiation, with its relatively long wavelength and low photon energy, produces effects in tissue similar to those of microwaves—heating—but the penetration is much less than for microwaves. Infrared is absorbed mostly by the top layer of your skin and simply warms you up, as you know from sitting in the sun or under a heat lamp. The wave picture is generally most appropriate for infrared.

In contrast, ultraviolet photons have enough energy to interact with molecules in entirely different ways, ionizing molecules and breaking molecular bonds. The cells in skin are altered by ultraviolet radiation, causing sun tanning and sun burning. DNA molecules can be permanently damaged by ultraviolet radiation. There is a sharp threshold for such damage at 290 nm (corresponding to 4.3 eV photon energy). At longer wavelengths, damage to cells is slight; at shorter wavelengths, it is extensive. The interactions of ultraviolet radiation with matter are best understood from the photon perspective, with the absorption of each photon being associated with a particular molecular event.

Visible light is at a transition point in the electromagnetic spectrum. Your studies of wave optics in Chapter 17 showed you that light has a wave nature. At the same time, the energy of photons of visible light is large enough to cause molecular transitions—which is how your eye detects light. The bending of light by the lens of the eye requires us to think of light as a wave, but the detection of light by the cells in the retina requires us to think of light as photons. When we work with visible light, we will often move back and forth between the wave and photon models.

EXAMPLE 25.11 Finding the photon energy for ultraviolet light

Ultraviolet radiation with a wavelength of 254 nm is used in germicidal lamps. What is the photon energy in eV for such a lamp?

SOLVE The photon energy is $E = hf$:

$$E = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J} \cdot \text{s})(3.00 \times 10^8 \text{ m/s})}{254 \times 10^{-9} \text{ m}}$$
$$= 7.83 \times 10^{-19} \text{ J}$$

In eV, this is

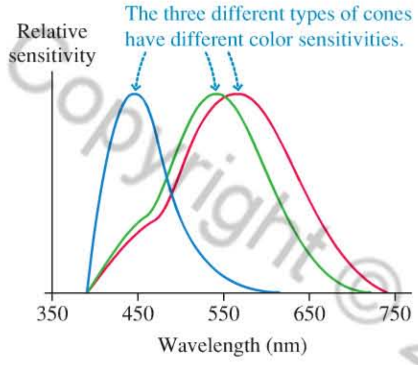
$$E = 7.83 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} = 4.89 \text{ eV}$$

ASSESS Table 25.1 shows that this energy is sufficient to break the bonds in a water molecule. It will be enough energy to break other bonds as well, leading to damage on a cellular level.

Color Vision

The cones, the color-sensitive cells in the retina of the eye, each contain one of three slightly different forms of a light-sensitive photopigment. A single photon of light can trigger a reaction in a photopigment molecule, which ultimately leads to a signal being produced by a cell in the retina. The energy of the photon must be matched to the energy of a molecular transition for absorption of the photon energy to take place. Each photopigment has a range of photon energies to which it is sensitive. Our color vision is a result of the differential response of three types of cones containing three slightly different pigments, shown in FIGURE 25.42.

FIGURE 25.42 The sensitivity of different cones in the human eye.



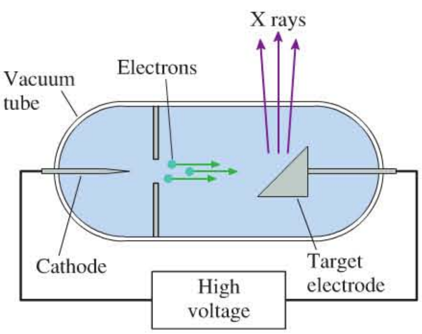
Humans have three types of cone in the eye, mice have two, and chickens four—giving a chicken keener color vision than a human. The three color photopigments that bees possess give them excellent color vision, but a bee's color sense is different from a human's. The peak sensitivities of a bee's photopigments are in the yellow, blue, and ultraviolet regions of the spectrum. A bee can't see the red of a rose, but it is quite sensitive to ultraviolet wavelengths well beyond the range of human vision. The flower in the right-hand photo at the start of the chapter looks pretty to us, but its coloration is really intended for other eyes. The ring of ultraviolet-absorbing pigments near the center of the flower, which is invisible to humans, helps bees zero in on the pollen.

X Rays and Gamma Rays

At the highest energies of the electromagnetic spectrum we find x rays and gamma rays. There is no sharp dividing line between these two regions of the spectrum; the difference is the source of radiation. High-energy photons emitted by electrons are called x rays. If the source is a nuclear process, we call them gamma rays.

We will look at the emission of x rays in atomic processes and gamma rays in nuclear processes in Part VII. For now, we will focus on the "artificial" production of x rays in an x-ray tube, such as the one shown in FIGURE 25.43. Electrons are emitted from a cathode and accelerated to a kinetic energy of several thousand eV by the electric field between two electrodes connected to a high-voltage power supply. The electrons make a sudden stop when they hit a metal target electrode. The rapid deceleration of an electron can cause the emission of a single photon with a significant fraction of the electron's kinetic energy. These photons, with energies well in excess of 1000 eV, are x rays. The x rays pass through a window in the tube and then may be used to produce an image or to treat a disease.

FIGURE 25.43 A simple x-ray tube.



EXAMPLE 25.12 Determining x-ray energies

An x-ray tube used for medical work has an accelerating voltage of 30 kV. What is the maximum energy of an x-ray photon that can be produced in this tube? What is the wavelength of this x ray?

SOLVE An electron accelerated through a potential difference of 30 kV acquires a kinetic energy of 30 keV. When this electron hits the metal target and stops, energy may be converted to an x ray. The maximum energy that could be converted is 30 keV, so this is the maximum possible energy of an x-ray photon from the tube. In joules, this energy is

$$E = 30 \times 10^3 \text{ eV} \times \frac{1.60 \times 10^{-19}\text{ J}}{1 \text{ eV}} = 4.8 \times 10^{-15}\text{ J}$$

For electromagnetic waves, $c = f\lambda$, so we can calculate

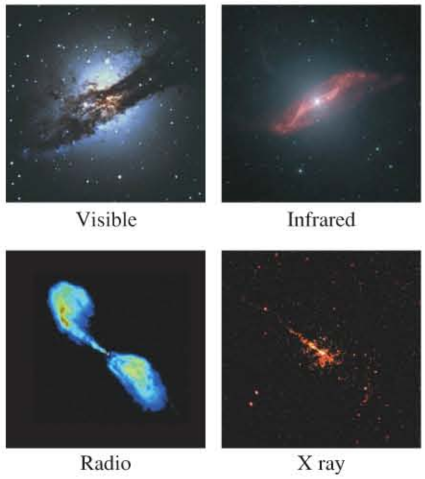
$$\lambda = \frac{c}{f} = \frac{c}{E/h} = \frac{hc}{E} = \frac{(6.63 \times 10^{-34}\text{ J}\cdot\text{s})(3.00 \times 10^8\text{ m/s})}{4.8 \times 10^{-15}\text{ J}}$$
$$= 4.1 \times 10^{-11}\text{ m} = 0.041\text{ nm}$$

ASSESS This is a very short wavelength, comparable to the spacing between atoms in a solid.

X rays and gamma rays (and the short-wavelength part of the ultraviolet spectrum) are **ionizing radiation;** the individual photons have sufficient energy to ionize atoms. When such radiation strikes tissue, the resulting ionization can produce cellular damage. When people speak of "radiation" they often mean "ionizing radiation."

X rays and gamma rays are very penetrating, but the absorption of these high-energy photons is greater in materials made of atoms with more electrons. This is why x rays are used in medical and dental imaging. The calcium in bones has many more electrons and thus is much more absorbing than the hydrogen, carbon, and oxygen that make up most of our soft tissue, so we can use x rays to image bones and teeth.

At several points in this chapter we have hinted at places where a full understanding of the phenomena requires some new physics. We have used the photon model of electromagnetic waves, and we have mentioned that nuclear processes can give rise to gamma rays. There are other questions that we did not raise, such as why the electromagnetic spectrum of a hot object has the shape that it does. These puzzles began to arise in the late 1800s and early 1900s, and it soon became clear that the physics of Newton and Maxwell was not sufficient to fully describe the nature of matter and energy. Some new rules, some new models, were needed. We will return to these puzzles as we begin to explore the exciting notions of quantum physics in Part VII.



▶ **Seeing the universe in a different light** These four images of the Centaurus A galaxy have the same magnification and orientation, but they are records of different types of electromagnetic waves. (All but the visible-light image are false-color images.) The visible-light image shows a dark dust lane cutting across the galaxy. In the infrared, this dust lane glows quite brightly—telling us that the dust particles are hot. The radio and x-ray images show jets of matter streaming out of the galaxy's center, hinting at the presence of a massive black hole. Views of the cosmos beyond the visible range are important tools of modern astronomy.

STOP TO THINK 25.6 A group of four stars, all the same size, have the four different surface temperatures given below. Which of these stars emits the most red light?

A. 3000 K B. 4000 K C. 5000 K D. 6000 K

INTEGRATED EXAMPLE 25.13 Space circuits

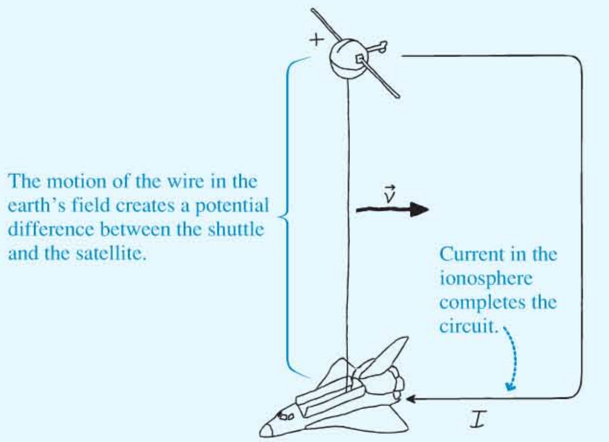
The very upper part of the atmosphere, where the Space Shuttle orbits, is called the *ionosphere*. The few atoms and molecules that remain at this altitude are mostly ionized by intense ultraviolet radiation from the sun. The thin gas of the ionosphere thus consists largely of positive ions and negative electrons, so it can carry an electric current. This was crucial to the operation of the tethered satellite system that was tested on the Space Shuttle in the 1990s. As described in the chapter, a probe was deployed on a conducting wire that tethered the probe at a great distance from the craft. As the Space Shuttle orbited, the wire moved through the earth's magnetic field, creating a potential difference between the ends of the wire. Charge flowing through the ionosphere back to the shuttle created a complete circuit.

In the final test of the tethered satellite system, a potential difference of 3500 V was generated across 20 km of cable as the shuttle orbited at 7800 m/s.

a. To produce the noted potential difference, what was the component of the magnetic field perpendicular to the wire?
b. The 3500 V potential created a current of 480 mA in the ionosphere. What was the total resistance of the circuit thus formed?
c. How much power was dissipated in this circuit?
d. What is the drag force on the wire due to its motion in the earth's field?
e. The ionization of the upper atmosphere is due to solar radiation at wavelengths of 95 nm and shorter. In what part of the spectrum is this radiation? What is the lowest-energy photon, in eV, that contributes to the ionization?

PREPARE The motion of the wire connecting the tethered satellite to the Space Shuttle leads to a motional emf that drives a current through this wire and back through the ionosphere. **FIGURE 25.44** shows how we can model this process as an electric circuit. We know the voltage and the current in this circuit, so we can find the resistance and the power. Because the wire carries a current, the earth's field will exert a force on it, which is the drag force we are asked to find.

FIGURE 25.44 The tethered satellite circuit.



Continued

SOLVE a. We know the magnitude of the velocity and the length of the wire, so we can use the equation for the motional emf, Equation 25.3, to find the magnitude of the component of the field perpendicular to the wire:

$$B = \frac{\mathcal{E}}{vl} = \frac{3500\,\text{V}}{(7800\text{ m/s})(20 \times 10^3\text{ m})} = 2.2 \times 10^{-5}\text{ T} = 22\ \mu\text{T}$$

b. The 3500 V potential difference produced a current of 480 mA. From Ohm's law, the resistance of the circuit was thus

$$R = \frac{\Delta V}{I} = \frac{3500\text{ V}}{480 \times 10^{-3}\text{ A}} = 7300\ \Omega$$

c. We know the voltage and the current, so we can compute the power:

$$P = I\,\Delta V = (0.48\text{ A})(3500\text{ V}) = 1700\text{ W}$$

d. The component of the magnetic field perpendicular to the current-carrying wire exerts a drag force on the wire. We learned in Chapter 24 that the force on a current-carrying wire is $F = IlB$. Thus

$$F = IlB = (0.48\text{ A})(20 \times 10^3\text{ m})(2.2 \times 10^{-5}\text{ T}) = 0.21\text{ N}$$

e. Radiation with wavelengths of 95 nm and shorter is in the ultraviolet region of the spectrum. The lowest-energy photon in this region has the lowest frequency and thus the longest wavelength—namely, 95 nm. The frequency is

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^8\text{ m/s}}{95 \times 10^{-9}\text{ m}} = 3.2 \times 10^{15}\text{ Hz}$$

The photon energy is then given by Equation 25.21:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34}\text{ J}\cdot\text{s})(3.1 \times 10^{15}\text{ Hz})$$
$$= 2.1 \times 10^{-18}\text{ J}$$

Converting to eV, we find

$$E_{\text{photon}} = 2.1 \times 10^{-18}\text{ J} \times \frac{1\text{ eV}}{1.6 \times 10^{-19}\text{ J}} = 13\text{ eV}$$

ASSESS We have many good chances to check our work to verify that it makes sense. First, the field component that we calculate is about half the value we typically use for the earth's field, which seems reasonable—we'd be suspicious if the field we calculated was more than the earth's field.

The product of the drag force and the speed is the power dissipated by the drag force:

$$P = Fv = (0.22\text{ N})(7800\text{ m/s}) = 1700\text{ W}$$

This is exactly what we found for the electric power dissipated in the circuit, a good check on our work. The two values must be equal, as they are.

A final check on our work is the value we calculate for the photon energy. Table 25.1 shows that it takes about 13 eV to ionize a hydrogen atom. Photons with wavelengths shorter than 95 nm are able to ionize hydrogen atoms, so it seems likely they would also ionize the nitrogen and oxygen molecules of the upper atmosphere.

SUMMARY

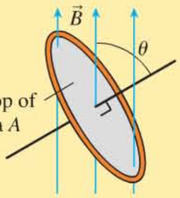
The goal of Chapter 25 has been to understand the nature of electromagnetic induction and electromagnetic waves.

GENERAL PRINCIPLES

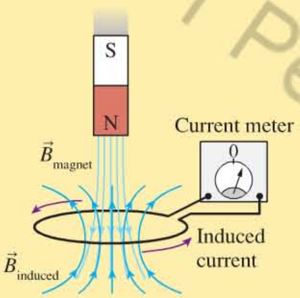
Electromagnetic Induction

The **magnetic flux** measures the amount of magnetic field passing through a surface:

$$\Phi = AB\cos\theta$$



Lenz's law specifies that there is an induced current in a closed conducting loop if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the *change* in flux.



Faraday's law specifies the magnitude of the induced emf in a closed loop:

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

Multiply by N for an N-turn coil.

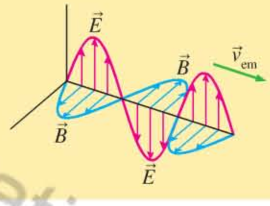
The size of the induced current is

$$I = \frac{\mathcal{E}}{R}$$

Electromagnetic Waves

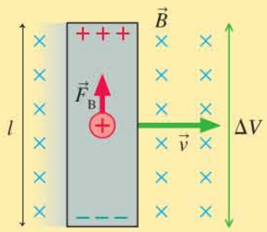
An electromagnetic wave is a self-sustaining oscillation of electric and magnetic fields.

- The wave is a transverse wave with $\vec{E}$, $\vec{B}$, and $\vec{v}$ mutually perpendicular.
- The wave propagates with speed
$$v_{\text{em}} = c = \frac{1}{\sqrt{\epsilon_0\mu_0}} = 3.00 \times 10^8 \text{ m/s}$$
- The wavelength, frequency, and speed are related by
$$c = f\lambda$$
- The amplitudes of the fields are related by
$$E_0 = cB_0$$



IMPORTANT CONCEPTS

Motional emf



The motion of a conductor through a magnetic field produces a force on the charges. The separation of charges leads to an emf:

$$\mathcal{E} = vlB$$

The photon model

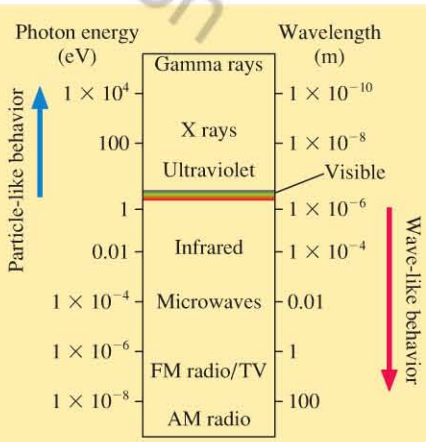
Electromagnetic waves appear to be made of discrete units called photons. The energy of a photon of frequency f is

$$E = hf$$

This photon view becomes increasingly important as the photon energy increases.

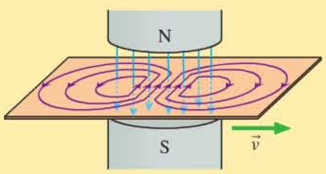
The electromagnetic spectrum

Electromagnetic waves come in a wide range of wavelengths and photon energies.



APPLICATIONS

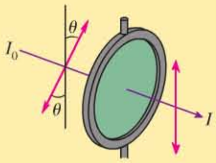
A changing flux in a solid conductor creates **eddy currents.**



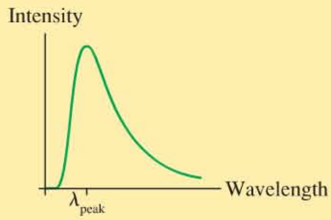
The plane of the electric field of an electromagnetic wave defines its **polarization.** The intensity of polarized light transmitted through a polarizing filter is given by **Malus's law:**

$$I = I_0\cos^2\theta$$

where θ is the angle between the electric field and the polarizer axis.



Thermal radiation has a peak wavelength that depends on an object's temperature according to **Wien's law:**



$$\lambda_{\text{peak}}(\text{in nm}) = \frac{2.9 \times 10^6 \text{ nm}\cdot\text{K}}{T}$$

For homework assigned on MasteringPhysics, go to www.masteringphysics.com

Problem difficulty is labeled as | (straightforward) to ||||| (challenging).

Problems labeled INT integrate significant material from earlier chapters; BIO are of biological or medical interest.

VIEW ALL SOLUTIONS

QUESTIONS

Conceptual Questions

1. The world's strongest magnet can produce a steady field of 45 T. If a circular wire loop of radius 10 cm were held in this magnetic field, what current would be induced in the loop?
2. BIO The rapid vibration accompanying the swimming motions of mayflies has been measured by gluing a small magnet to a swimming mayfly and recording the emf in a small coil of wire placed nearby. Explain how this technique works.
3. Parts a through f of Figure Q25.3 show one or more metal wires sliding on fixed metal rails in a magnetic field. For each, determine if the induced current is clockwise, counterclockwise, or is zero.

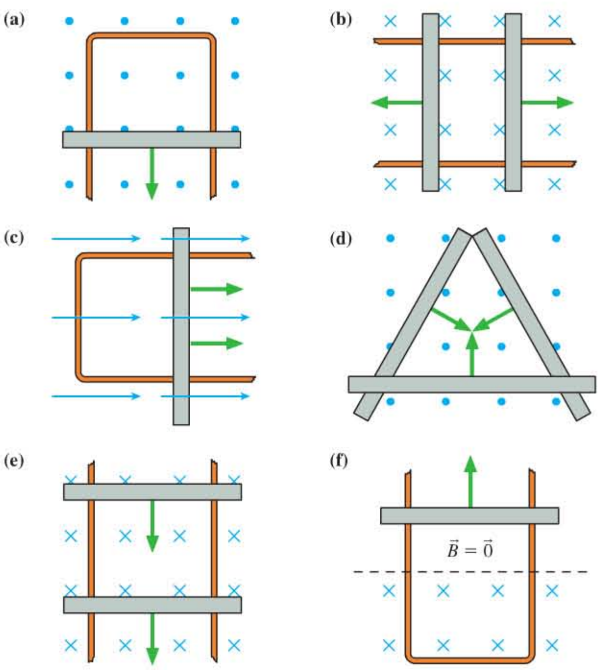


FIGURE Q25.3

4. Figure Q25.4 shows four different loops in a magnetic field. The numbers indicate the lengths of the sides and the strength of the field. Rank in order the magnetic fluxes Φ_1 through Φ_4, from the largest to the smallest. Some may be equal. Explain.

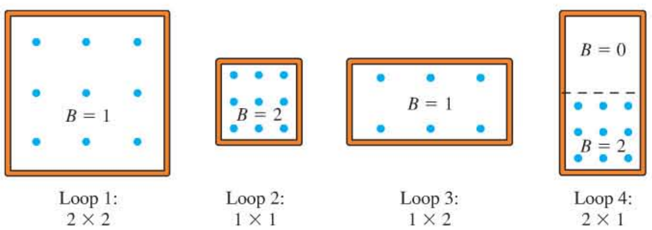


FIGURE Q25.4

5. Figure Q25.5 shows four different circular loops that are perpendicular to the page. The radius of loops 3 and 4 is twice that of loops 1 and 2. The magnetic field is the same for each. Rank in order the magnetic fluxes Φ_1 through Φ_4, from the largest to the smallest. Some may be equal. Explain.

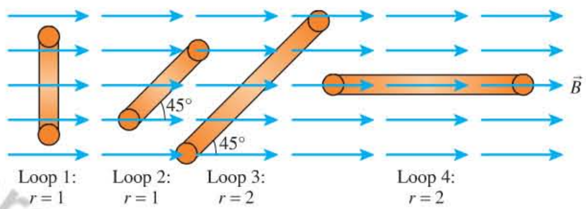


FIGURE Q25.5

6. A circular loop rotates at constant speed about an axle through the center of the loop. Figure Q25.6 shows an edge view and defines the angle ϕ, which increases from 0° to 360° as the loop rotates.
   a. At what angle or angles is the magnetic flux a maximum?
   b. At what angle or angles is the magnetic flux a minimum?
   c. At what angle or angles is the magnetic flux *changing* most rapidly?

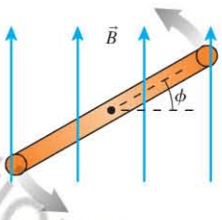


FIGURE Q25.6

7. The power lines that run through your neighborhood carry *alternating currents* that reverse direction 120 times per second. As the current changes, so does the magnetic field around a line. Suppose you wanted to put a loop of wire up near the power line to extract power by "tapping" the magnetic field. Sketch a picture of how you would orient the coil of wire next to a power line to develop the maximum emf in the coil. (Note that this is dangerous and illegal, and not something you should try.)
8. The magnetic flux passing through a coil of wire varies as shown in Figure Q25.8. During which time interval(s) will an induced current be present in the coil? Explain.

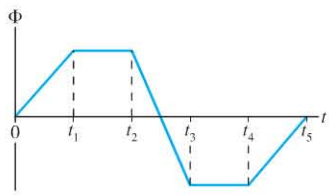


FIGURE Q25.8

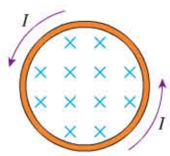


FIGURE Q25.9

9. There is a counterclockwise induced current in the conducting loop shown in Figure Q25.9. Is the magnetic field inside the loop increasing in strength, decreasing in strength, or steady?

10. Cars on the "Tower of Doom" carnival ride are dropped from a great height, giving riders a few seconds of free fall. To stop the cars, strong permanent magnets attached to the bottoms of the cars pass very close to aluminum vanes sticking up from the bottom of the track. Explain how this braking system works.
11. A magnet dropped through a clear plastic tube accelerates as expected in free fall. If dropped through an aluminum tube of exactly the same length and diameter, the magnet falls much more slowly. Explain the behavior of the second magnet.
12. The conducting loop in Figure Q25.12 is moving into the region between the magnetic poles shown.
    a. Is the induced current (viewed from above) clockwise or counterclockwise?
    b. Is there an attractive magnetic force that tends to pull the loop in, like a magnet pulls on a paper clip? Or do you need to push the loop in against a repulsive force?

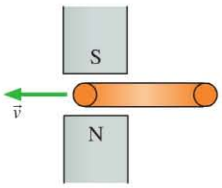


FIGURE Q25.12

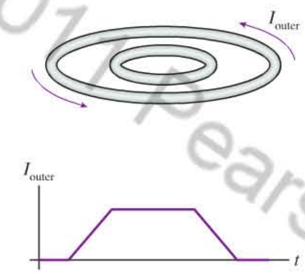


FIGURE Q25.13

13. Figure Q25.13 shows two concentric, conducting loops. We will define a counterclockwise current (viewed from above) to be positive, a clockwise current to be negative. The graph shows the current in the outer loop as a function of time. Sketch a graph that shows the induced current in the inner loop. Explain.
14. Two loops of wire are stacked vertically, one above the other, as shown in Figure Q25.14. Does the upper loop have a clockwise current, a counterclockwise current, or no current at the following times? Explain your reasoning.


FIGURE Q25.14

    a. Before the switch is closed
    b. Immediately after the switch is closed
    c. Long after the switch is closed
    d. Immediately after the switch is reopened
15. A loop of wire is horizontal. A bar magnet is pushed toward the loop from below, along the axis of the loop, as shown in Figure Q25.15.
    a. In what direction is the current in the loop? Explain.
    b. Is there a magnetic force on the loop? If so, in which direction? Explain.

    Hint: Recall that a current loop is a magnetic dipole.

    c. Is there a magnetic force on the magnet? If so, in which direction?

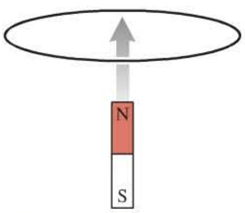


FIGURE Q25.15

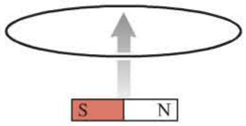


FIGURE Q25.16

16. A bar magnet is pushed toward a loop of wire, as shown in Figure Q25.16. Is there a current in the loop? If so, in which direction? If not, why not?
17. A conducting loop around a region of strong magnetic field contains two light bulbs, as shown in Figure Q25.17. The wires connecting the bulbs are ideal. The magnetic field is increasing rapidly.
    a. Do the bulbs glow? Why or why not?
    b. If they glow, which bulb is brighter? Or are they equally bright? Explain.

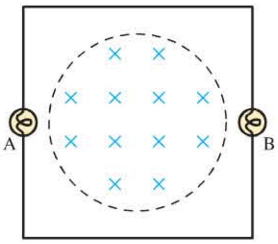


FIGURE Q25.17

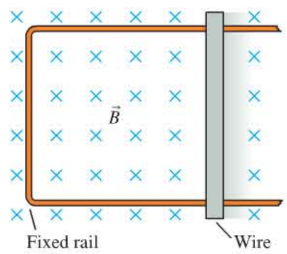
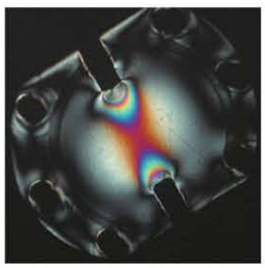


FIGURE Q25.18

18. A metal wire is resting on a U-shaped conducting rail, as shown in Figure Q25.18. The rail is fixed in position, but the wire is free to move.
    a. If the magnetic field is increasing in strength, what does the wire do? Does it remain in place? Or does it move to the right or left, or up or down, or out of the plane of the page (breaking contact with the rail)? Does it rotate clockwise or counterclockwise? Does it both move and rotate? Explain.
    b. If the magnetic field is decreasing in strength, what does the wire do?
19. Though sunlight is unpolarized, the light that reflects from smooth surfaces may be partially polarized in the direction parallel to the plane of the reflecting surface. How should the long axis of the polarizing molecules in polarized sunglasses be oriented—vertically or horizontally—to reduce the glare from a horizontal surface such as a road or a lake?
20. Two polarizers are oriented with axes at 90°, so no light passes through the pair. A piece of plastic is placed between the two. If the plastic is stressed, by being squeezed, light that passes through the first polarizer and the plastic now passes through the second polarizer. The dark and light lines allow the pattern of stress to be determined. What effect does the stressed plastic have on the polarization of light passing through it?


With polarizing filters


Without polarizing filters

21. Old-fashioned roof-mounted television antennas were designed to pick up signals across a broad frequency range. Explain why these antennas had metal bars of many different lengths.

22. An AM radio detects the oscillating magnetic field of the radio wave with an antenna consisting of a coil of wire wrapped around a ferrite bar, as shown in Figure Q25.22. Ferrite is a magnetic material that "amplifies" the magnetic field of the wave.
   a. Explain how the radio antenna detects the magnetic field of the radio wave.
   b. If a radio station is located due north of you, how must the ferrite bar be oriented for best reception? Assume that the station broadcasts with a vertical antenna like the one shown in Figure 25.37.

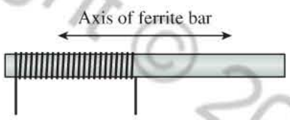


FIGURE Q25.22

23. Three laser beams have wavelengths $\lambda_1 = 400$ nm, $\lambda_2 = 600$ nm, and $\lambda_3 = 800$ nm. The power of each laser beam is 1 W.
   a. Rank in order, from largest to smallest, the photon energies E_1, E_2, and E_3 in these three laser beams. Explain.
   b. Rank in order, from largest to smallest, the number of photons per second N_1, N_2, and N_3 delivered by the three laser beams. Explain.
24. The intensity of a beam of light is increased but the light's frequency is unchanged. As a result, which of the following (perhaps more than one) are true? Explain.
   A. The photons travel faster.
   B. Each photon has more energy.
   C. The photons are larger.
   D. There are more photons per second.
25. The frequency of a beam of light is increased but the light's intensity is unchanged. As a result, which of the following (perhaps more than one) are true? Explain.
   A. The photons travel faster.
   B. Each photon has more energy.
   C. There are fewer photons per second.
   D. There are more photons per second.
26. Arc welding uses electric current to make an extremely hot electric arc that can melt metal. The arc emits ultraviolet light that can cause sunburn and eye damage if a welder is not wearing protective gear. Why does the arc give off ultraviolet light?

Multiple-Choice Questions

27. | A circular loop of wire has an area of 0.30 m^2. It is tilted by 45° with respect to a uniform 0.40 T magnetic field. What is the magnetic flux through the loop?
   A. 0.085 T · m^2
   B. 0.12 T · m^2
   C. 0.38 T · m^2
   D. 0.75 T · m^2
   E. 1.3 T · m^2
28. | In Figure Q25.28, a square loop is rotating in the plane of the page around an axis through its center. A uniform magnetic field is directed into the page. What is the direction of the induced current in the loop?
   A. Clockwise.
   B. Counterclockwise.
   C. There is no induced current.

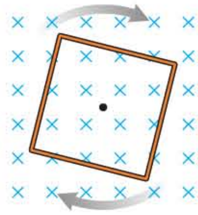


FIGURE Q25.28

29. | A diamond-shaped loop of wire is pulled at a constant velocity through a region where the magnetic field is directed into the paper in the left half and is zero in the right half, as shown in Figure Q25.29. As the loop moves from left to right, which graph best represents the induced current in the loop as a function of time? Let a clockwise current be positive and a counterclockwise current be negative.

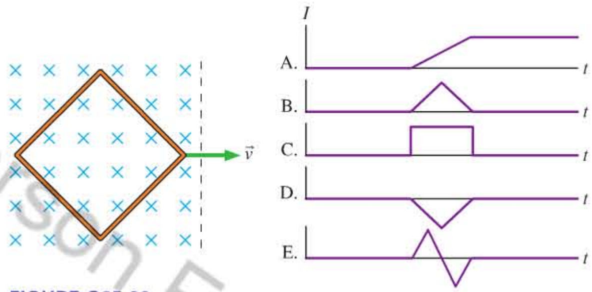


FIGURE Q25.29

30. || Figure Q25.30 shows a triangular loop of wire in a uniform magnetic field. If the field strength changes from 0.30 to 0.10 T in 50 ms, what is the induced emf in the loop?
   A. 0.08 V
   B. 0.12 V
   C. 0.16 V
   D. 0.24 V
   E. 0.36 V

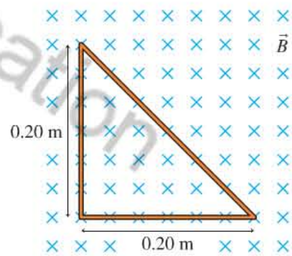


FIGURE Q25.30

31. || A device called a *flip coil* can be used to measure the earth's magnetic field. The coil has 100 turns and an area of 0.010 m^2. It is oriented with its plane perpendicular to the earth's magnetic field, then flipped 180° so the field goes through the coil in the opposite direction. The earth's magnetic field is 0.050 mT, and the coil flips over in 0.50 s. What is the average emf induced in the coil during the flip?
   A. 0.050 mV B. 0.10 mV
   C. 0.20 mV D. 1.0 mV
32. | The electromagnetic waves that carry FM radio range in frequency from 87.9 MHz to 107.9 MHz. What is the range of wavelengths of these radio waves?
   A. 500–750 nm B. 0.87–91.08 m
   C. 2.78–3.41 m D. 278–341 m
   E. 234–410 km
33. | A spacecraft in orbit around the moon measures its altitude by reflecting a pulsed 10 MHz radio signal from the surface. If the spacecraft is 10 km high, what is the time between the emission of the pulse and the detection of the echo?
   A. 33 ns B. 67 ns
   C. 33 μs D. 67 μs

34. | A 6.0 mW vertically polarized laser beam passes through a polarizing filter whose axis is 75° from vertical. What is the laser-beam power after passing through the filter?
A. 0.40 mW B. 1.0 mW
C. 1.6 mW D. 5.6 mW

35. | Communication with submerged submarines via radio waves is difficult because seawater is conductive and absorbs electromagnetic waves. Penetration into the ocean is greater at longer wavelengths, so the United States has radio installations that transmit at 76 Hz for submarine communications. What is the approximate wavelength of those extremely low-frequency waves?
A. 500 km B. 1000 km
C. 2000 km D. 4000 km

36. || How many photons are emitted during 5.0 s of operation of a red laser pointer? The device outputs 2.8 mW at a 635 nm wavelength.
A. 4.5×10^{10} B. 4.5×10^{11}
C. 4.5×10^{15} D. 4.5×10^{16}

PROBLEMS

Section 25.1 Induced Currents

Section 25.2 Motional emf

1. | A potential difference of 0.050 V is developed across the 10-cm-long wire in Figure P25.1 as it moves through a magnetic field at 5.0 m/s. The magnetic field is perpendicular to the axis of the wire. What are the direction and strength of the magnetic field?

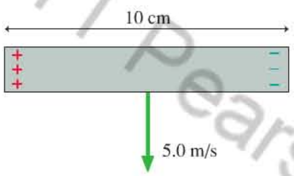


FIGURE P25.1

2. || A scalloped hammerhead shark swims at a steady speed of 1.5 m/s with its 85-cm-wide head perpendicular to the earth's 50 μT magnetic field. What is the magnitude of the emf induced between the two sides of the shark's head?
BIO

3. || A 10-cm-long wire is pulled along a U-shaped conducting rail in a perpendicular magnetic field. The total resistance of the wire and rail is 0.20 Ω. Pulling the wire with a force of 1.0 N causes 4.0 W of power to be dissipated in the circuit.
a. What is the speed of the wire when pulled with a force of 1.0 N?
b. What is the strength of the magnetic field?

4. | Figure P25.4 shows a 15-cm-long metal rod pulled along two frictionless, conducting rails at a constant speed of 3.5 m/s. The rails have negligible resistance, but the rod has a resistance of 0.65 Ω.
a. What is the current induced in the rod?
b. What force is required to keep the rod moving at a constant speed?

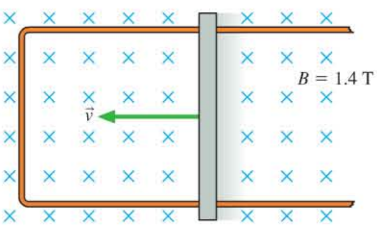


FIGURE P25.4

5. ||| A 50 g horizontal metal bar, 12 cm long, is free to slide up and down between two tall, vertical metal rods that are 12 cm apart. A 0.060 T magnetic field is directed perpendicular to the plane of the rods. The bar is raised to near the top of the rods, and a 1.0 Ω resistor is connected across the two rods at the top. Then the bar is dropped. What is the terminal speed at which the bar falls? Assume the bar remains horizontal and in contact with the rods at all times.

6. || A delivery truck with 2.8-m-high aluminum sides is driving west at 75 km/hr in a region where the earth's magnetic field is $\vec{B} = (5.0 \times 10^{-5}$ T, north).
a. What is the potential difference between the top and the bottom of the truck's side panels?
b. Will the tops of the panels be positive or negative relative to the bottoms?

Section 25.3 Magnetic Flux

7. | Figure P25.7 is an edge-on view of a 10-cm-diameter circular loop rotating in a uniform 0.050 T magnetic field. What is the magnetic flux through the loop when θ is 0°, 30°, 60°, and 90°?

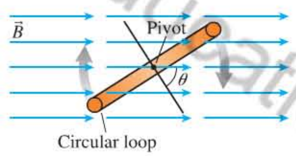


FIGURE P25.7

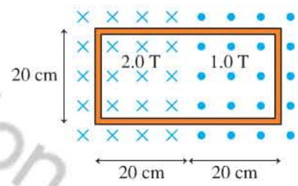


FIGURE P25.8

8. || What is the magnetic flux through the loop shown in Figure P25.8?

9. ||| The 2.0-cm-diameter solenoid in Figure P25.9 passes through the center of a 6.0-cm-diameter loop. The magnetic field inside the solenoid is 0.20 T. What is the magnetic flux through the loop (a) when it is perpendicular to the solenoid and (b) when it is tilted at a 60° angle?

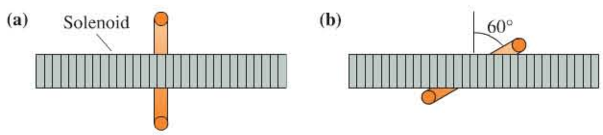


FIGURE P25.9

10. || At a typical location in the United States, the earth's magnetic field has a magnitude of 5.0×10^{-5} T and is at a 65° angle from the horizontal. What is the flux through the 22 cm × 28 cm front cover of your textbook if it is flat on your desk?

11. | The metal equilateral triangle in Figure P25.11, 20 cm on each side, is halfway into a 0.10 T magnetic field.
a. What is the magnetic flux through the triangle?
b. If the magnetic field strength decreases, what is the direction of the induced current in the triangle?

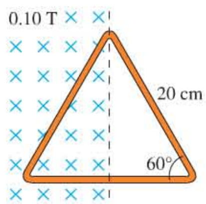


FIGURE P25.11

Section 25.4 Faraday's Law

12. | Figure P25.12 shows a 10-cm-diameter loop in three different magnetic fields. The loop's resistance is 0.10 Ω. For each case, determine the induced emf, the induced current, and the direction of the current.

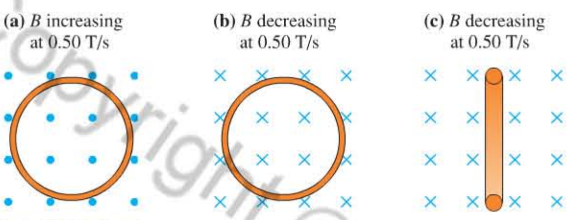


FIGURE P25.12

13. || A loop of wire is perpendicular to a magnetic field. Rank, from greatest to least, the magnitudes of the loop's induced emf for the following situations:
    A. The magnetic field strength increases from 0 to 1 T in 6 s.
    B. The magnetic field strength increases from 1 T to 4 T in 2 s.
    C. The magnetic field strength remains at 4 T for 1 min.
    D. The magnetic field strength decreases from 4 T to 3 T in 4 s.
    E. The magnetic field strength decreases from 3 T to 0 T in 1 s.
14. || Patients undergoing an MRI occasionally report seeing flashes of light. Some practitioners assume that this results from electric stimulation of the eye by the emf induced by the rapidly changing fields of an MRI solenoid. We can do a quick calculation to see if this is a reasonable assumption. The human eyeball has a diameter of approximately 25 mm. Rapid changes in current in an MRI solenoid can produce rapid changes in field, with $\Delta B/\Delta t$ as large as 50 T/s. What emf would this induce in a loop circling the eyeball? How does this compare to the 15 mV necessary to trigger an action potential?
BIO
15. ||| A 1000-turn coil of wire 2.0 cm in diameter is in a magnetic field that drops from 0.10 T to 0 T in 10 ms. The axis of the coil is parallel to the field. What is the emf of the coil?
16. || The loop in Figure P25.16 has an induced current as shown. The loop has a resistance of 0.10 Ω. Is the magnetic field strength increasing or decreasing? What is the rate of change of the field, $\Delta B/\Delta t$?

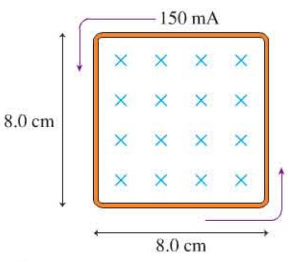


FIGURE P25.16

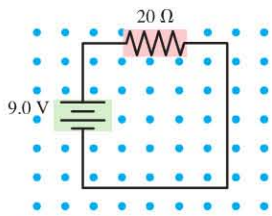


FIGURE P25.17

17. || The circuit of Figure P25.17 is a square 5.0 cm on a side. The magnetic field increases steadily from 0 T to 0.50 T in 10 ms. What is the current in the resistor during this time?
18. ||| A 5.0-cm-diameter loop of wire has resistance 1.2 Ω. A nearby solenoid generates a uniform magnetic field perpendicular to the loop that varies with time as shown in Figure P25.18. Graph the magnitude of the current in the loop over the same time interval.

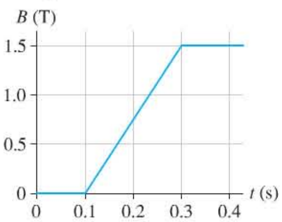


FIGURE P25.18

Section 25.5 Induced Fields and Electromagnetic Waves

Section 25.6 Properties of Electromagnetic Waves

19. | What is the electric field amplitude of an electromagnetic wave whose magnetic field amplitude is 2.0 mT?
20. | What is the magnetic field amplitude of an electromagnetic wave whose electric field amplitude is 10 V/m?
21. || A microwave oven operates at 2.4 GHz with an intensity inside the oven of 2500 W/m^2. What are the amplitudes of the oscillating electric and magnetic fields?
22. || The maximum allowed leakage of microwave radiation from a microwave oven is 5.0 mW/cm^2. If microwave radiation outside an oven has the maximum value, what is the amplitude of the oscillating electric field?
23. ||| A typical helium-neon laser found in supermarket checkout scanners emits 633-nm-wavelength light in a 1.0-mm-diameter beam with a power of 1.0 mW. What are the amplitudes of the oscillating electric and magnetic fields in the laser beam?
24. | The magnetic field of an electromagnetic wave in a vacuum is $B_z = (3.0\ \mu\text{T})\sin((1.0 \times 10^7)x - 2\pi ft)$, where x is in m and t is in s. What are the wave's (a) wavelength, (b) frequency, and (c) electric field amplitude?
25. || The electric field of an electromagnetic wave in a vacuum is $E_y = (20\ \text{V/m})\sin((6.28 \times 10^8)x - 2\pi ft)$, where x is in m and t is in s. What are the wave's (a) wavelength, (b) frequency, and (c) magnetic field amplitude?
26. || A radio receiver can detect signals with electric field amplitudes as small as 300 μV/m. What is the intensity of the smallest detectable signal?
27. || A 200 MW laser pulse is focused with a lens to a diameter of 2.0 μm.
INT
    a. What is the laser beam's electric field amplitude at the focal point?
    b. What is the ratio of the laser beam's electric field to the electric field that keeps the electron bound to the proton of a hydrogen atom? The radius of the electron's orbit is 0.053 nm.
28. ||| A radio antenna broadcasts a 1.0 MHz radio wave with 25 kW of power. Assume that the radiation is emitted uniformly in all directions.
    a. What is the wave's intensity 30 km from the antenna?
    b. What is the electric field amplitude at this distance?
29. || At what distance from a 10 W point source of electromagnetic waves is the electric field amplitude (a) 100 V/m and (b) 0.010 V/m?
30. | The intensity of a polarized electromagnetic wave is 10 W/m^2. What will be the intensity after passing through a polarizing filter whose axis makes the following angles with the plane of polarization? (a) $\theta = 0°$ (b) $\theta = 30°$ (c) $\theta = 45°$ (d) $\theta = 60°$ (e) $\theta = 90°$.
31. || Only 25% of the intensity of a polarized light wave passes through a polarizing filter. What is the angle between the electric field and the axis of the filter?
32. || A 200 mW horizontally polarized laser beam passes through a polarizing filter whose axis is 25° from vertical. What is the power of the laser beam as it emerges from the filter?
33. || The polarization of a helium-neon laser can change with time. The light from a 1.5 mW laser is initially horizontally polarized; as the laser warms up, the light changes to be vertically polarized. Suppose the laser beam passes through a polarizer whose axis is 30° from horizontal. By what percent does the light intensity transmitted through the polarizer decrease as the laser warms up?

Section 25.7 The Photon Model of Electromagnetic Waves

34. What is the energy (in eV) of a photon of visible light that has a wavelength of 500 nm?
35. What is the energy (in eV) of an x-ray photon that has a wavelength of 1.0 nm?
36. What is the wavelength of a photon whose energy is twice that of a photon with a 600 nm wavelength?
37. BIO One recent study has shown that x rays with a wavelength of 0.0050 nm can produce mutations in human cells.
    a. Calculate the energy in eV of a photon of radiation with this wavelength.
    b. Assuming that the bond energy holding together a water molecule is typical, use Table 25.1 to estimate how many molecular bonds could be broken with this energy.
38. BIO Rod cells in the retina of the eye detect light using a photopigment called rhodopsin. 1.8 eV is the lowest photon energy that can trigger a response in rhodopsin. What is the maximum wavelength of electromagnetic radiation that can cause a transition? In what part of the spectrum is this?
39. What is the energy of 1 mol of photons that have a wavelength of 1.0 μm?
40. BIO The thermal emission of the human body has maximum intensity at a wavelength of approximately 9.5 μm. What photon energy corresponds to this wavelength?
41. The intensity of electromagnetic radiation from the sun reaching the earth's upper atmosphere is 1.37 kW/m^2. Assuming an average wavelength of 680 nm for this radiation, find the number of photons per second that strike a 1.00 m^2 solar panel directly facing the sun on an orbiting satellite.
42. BIO The human eye can barely detect a star whose intensity at the earth's surface is 1.6×10^{-11} W/m^2. If the dark-adapted eye has a pupil diameter of 7.0 mm, how many photons per second enter the eye from the star? Assume the starlight has a wavelength of 550 nm.

Section 25.8 The Electromagnetic Spectrum

43. The spectrum of a glowing filament has its peak at a wavelength of 1200 nm. What is the temperature of the filament, in °C?
44. While using a dimmer switch to investigate a new type of incandescent light bulb, you notice that the light changes both its spectral characteristics and its brightness as the voltage is increased.
    a. If the wavelength of maximum intensity decreases from 1800 nm to 1600 nm as the bulb's voltage is increased, by how many °C does the filament temperature increase?
    b. By what factor does the total radiation from the filament increase due to this temperature change?
45. BIO The photon energies used in different types of medical x-ray imaging vary widely, depending upon the application. Single dental x rays use photons with energies of about 25 keV. The photon energy used for x-ray microtomography, a process that allows repeated imaging in single planes at varying depths within the sample, is 2.5 times greater. What are the wavelengths of the x rays used for these two purposes?

General Problems

46. A 10 cm $\times$ 10 cm square is bent at a 90° angle as shown in Figure P25.46. A uniform 0.050 T magnetic field points downward at a 45° angle. What is the magnetic flux through the loop?

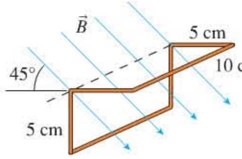


FIGURE P25.46

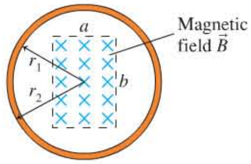


FIGURE P25.47

47. What is the magnetic flux through the loop shown in Figure P25.47?
48. a. A circular loop antenna has a diameter of 20 cm. If the plane of the loop is perpendicular to the earth's 50 μT magnetic field, what is the flux through the loop?
    b. What is the flux if the loop is rotated by 30°?
49. An 1.1-m-diameter MRI solenoid with a length of 2.4 m has a magnetic field of 1.5 T along its axis. If the current is turned off in a time of 1.2 s, what is the induced emf in one turn of the solenoid's windings?
50. A magnet and a coil are oriented as shown in Figure P25.50. The magnet is moved rapidly into the coil, held stationary in the coil for a short time, and then rapidly pulled back out of the coil. Sketch a graph showing the reading of the ammeter as a function of time. The ammeter registers a positive value when current goes into the "+" terminal.

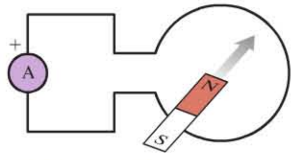


FIGURE P25.50

51. A wire loop with an area of 0.020 m^2 is in a magnetic field of 0.30 T directed at a 30° angle to the plane of the loop. If the field drops to zero in 45 ms, what is the average induced emf in the loop?
52. A 100-turn, 2.0-cm-diameter coil is at rest in a horizontal plane. A uniform magnetic field 60° away from vertical increases from 0.50 T to 1.50 T in 0.60 s. What is the induced emf in the coil?
53. A 25-turn, 10.0-cm-diameter coil is oriented in a vertical plane with its axis aligned east-west. A magnetic field pointing to the northeast decreases from 0.80 T to 0.20 T in 2.0 s. What is the emf induced in the coil?
54. BIO People immersed in strong unchanging magnetic fields occasionally report sensing a metallic taste. Some investigators suspect that motion in the constant field could produce a changing flux and a resulting emf that could stimulate nerves in the tongue. We can make a simple model to see if this is reasonable by imagining a somewhat extreme case. Suppose a patient having an MRI is immersed in a 3.0 T field along the axis of his body. He then quickly tips his head to the side, toward his right shoulder, tipping his head by 30° in the rather short time of 0.15 s. Estimate the area of the tongue; then calculate the emf that could be induced in a loop around the outside of the tongue by this motion of the head. How does this emf compare to the approximately 15 mV necessary to trigger an action potential? Does it seem reasonable to suppose that an induced emf is responsible for the noted effect?
55. INT A 20 cm length of 0.32-mm-diameter nichrome wire is welded into a circular loop. The loop is placed between the poles of an electromagnet, and a field of 0.55 T is switched on in a time of 15 ms. What is the induced current in the loop?
56. BIO INT Currents induced by rapid field changes in an MRI solenoid can, in some cases, heat tissues in the body, but under normal circumstances the heating is small. We can do a quick estimate to show this. Consider the "loop" of muscle tissue shown in Figure P25.56. This might be muscle circling the bone of

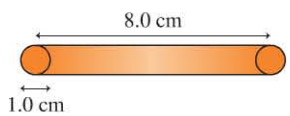


FIGURE P25.56

your arm or leg. Muscle tissue is not a great conductor, but current will pass through muscle and so we can consider this a conducting loop with a rather high resistance. Suppose the magnetic field along the axis of the loop drops from 1.6 T to 0 T in 0.30 s, as it might in an MRI solenoid.

a. How much energy is dissipated in the loop?
b. By how much will the temperature of the tissue increase?

Assume that muscle tissue has resistivity $13\ \Omega \cdot \mathrm{m}$, density $1.1 \times 10^3\ \mathrm{kg/m^3}$, and specific heat $3600\ \mathrm{J/kg \cdot K}$.

57. ||| INT A 100-turn, 8.0-cm-diameter coil is made of 0.50-mm-diameter copper wire. A magnetic field is perpendicular to the coil. At what rate must B increase to induce a 2.0 A current in the coil?

58. || The loop in Figure P25.58 is being pushed into the 0.20 T magnetic field at 50 m/s. The resistance of the loop is $0.10\ \Omega$. What are the direction and magnitude of the current in the loop?

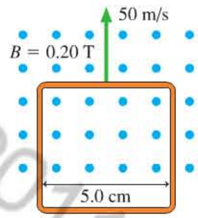


FIGURE P25.58

59. ||| INT A 20-cm-long, zero-resistance wire is pulled outward, on zero-resistance rails, at a steady speed of 10 m/s in a 0.10 T magnetic field. (See Figure P25.59.) On the opposite side, a $1.0\ \Omega$ carbon resistor completes the circuit by connecting the two rails. The mass of the resistor is 50 mg.

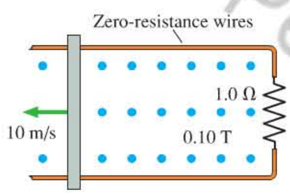


FIGURE P25.59

a. What is the induced current in the circuit?
b. How much force is needed to pull the wire at this speed?
c. How much does the temperature of the carbon increase if the wire is pulled for 10 s? The specific heat of carbon is $710\ \mathrm{J/kg \cdot K}$. Neglect thermal energy transfer out of the resistor.

60. |||| BIO INT A TMS (transcranial magnetic stimulation) device creates very rapidly changing magnetic fields. The field near a typical pulsed-field machine rises from 0 T to 2.5 T in 200 μs. Suppose a technician holds his hand near the device so that the axis of his 2.0-cm-diameter wedding band is parallel to the field.

a. What emf is induced in the ring as the field changes?
b. If the band is gold with a cross-section area of $4.0\ \mathrm{mm^2}$, what is the induced current?

Can you see why TMS technicians are advised to remove all jewelry?

61. || The 10-cm-wide, zero-resistance wire shown in Figure P25.61 is pushed toward the $2.0\ \Omega$ resistor at a steady speed of 0.50 m/s. The magnetic field strength is 0.50 T.

a. How big is the pushing force?
b. How much power does the pushing force supply to the wire?
c. What are the direction and magnitude of the induced current?
d. How much power is dissipated in the resistor?

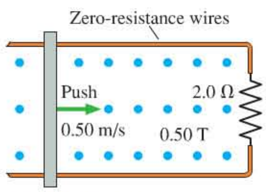


FIGURE P25.61

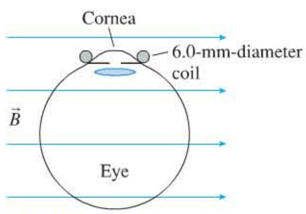


FIGURE P25.62

62. |||| BIO Experiments to study vision often need to track the movements of a subject's eye. One way of doing so is to have the subject sit in a magnetic field while wearing special contact lenses that have a coil of very fine wire circling the edge. A current is induced in the coil each time the subject rotates his eye. Consider an experiment in which a 20-turn, 6.0-mm-diameter coil of wire circles the subject's cornea while a 1.0 T magnetic field is directed as shown in Figure P25.62. The subject begins by looking straight ahead. What emf is induced in the coil if the subject shifts his gaze by 5.0° in 0.20 s?

63. ||| The filament in the center of a 100 W incandescent bulb emits approximately 4.0 W of visible light. If you assume that all of this light is emitted at a single wavelength, estimate the electric and magnetic field strength at the surface of the bulb.

64. || BIO INT A LASIK vision correction system uses a laser that emits 10-ns-long pulses of light, each with 2.5 mJ of energy. The laser is focused to a 0.85-mm-diameter circle. (a) What is the average power of each laser pulse? (b) What is the electric field strength of the laser light at the focus point?

65. | When the Voyager 2 spacecraft passed Neptune in 1989, it was 4.5×10^9 km from the earth. Its radio transmitter, with which it sent back data and images, broadcast with a mere 21 W of power. Assuming that the transmitter broadcast equally in all directions,

a. What signal intensity was received on the earth?
b. What electric field amplitude was detected?

(The received signal was slightly stronger than your result because the spacecraft used a directional antenna.)

66. || A new cordless phone emits 4.0 mW at 5.8 GHz. The manufacturer claims that the phone has a range of 100 feet. If we assume that the wave spreads out evenly with no obstructions, what is the electric field strength at the base unit 100 feet from the phone?

67. ||| 633-nm-wavelength light from a helium-neon laser is vertically polarized. Suppose a laser beam passes through a polarizer with its axis 45° from the vertical. What is the ratio of the laser beam's electric field strengths before and after the polarizer?

68. || In reading the instruction manual that came with your garage-door opener, you see that the transmitter unit in your car produces a 250 mW signal and that the receiver unit is supposed to respond to a radio wave of the correct frequency if the electric field amplitude exceeds 0.10 V/m. You wonder if this is really true. To find out, you put fresh batteries in the transmitter and start walking away from your garage while opening and closing the door. Your garage door finally fails to respond when you're 42 m away. Are the manufacturer's claims true?

69. ||| Unpolarized light passes through a vertical polarizing filter, emerging with an intensity I_0. The light then passes through a horizontal filter, which blocks all of the light; the intensity transmitted through the pair of filters is zero. Suppose a third polarizer with axis 45° from vertical is inserted between the first two. What is the transmitted intensity now?

70. | a. What is the wavelength of a gamma-ray photon with energy 1.0×10^{-13} J?
b. How many visible-light photons with a wavelength of 500 nm would you need to match the energy of this one gamma-ray photon?

71. | Gamma rays with the very high energy of 2.0×10^{13} eV are occasionally observed from distant astrophysical sources. What are the wavelength and frequency corresponding to this photon energy?

72. | A 1000 kHz AM radio station broadcasts with a power of 20 kW. How many photons does the transmitting antenna emit each second?

73. ‖ Fireflies emit flashes of light to communicate, directly converting chemical energy into the energy of visible-light photons. A firefly emits a 0.15-s-long pulse of light with an average wavelength of 590 nm. During the flash, the emitted power is 40 μW.
BIO
   a. What is the energy of one light photon having the average wavelength?
   b. Assume that all photons have the average wavelength. How many photons does the firefly emit during each flash?

74. |||| The human body has a surface area of approximately 1.8 m^2, a surface temperature of approximately 30°C, and a typical emissivity at infrared wavelengths of $e = 0.97$. If we make the approximation that all photons are emitted at the wavelength of peak intensity, how many photons per second does the body emit?
BIO

75. ||| For radio and microwaves, the depth of penetration into the human body is approximately proportional to $\sqrt{\lambda}$. If 27 MHz radio waves penetrate to a depth of 14 cm, estimate the depth of penetration of 2.4 GHz microwaves.
BIO

Passage Problems

The Metal Detector

Metal detectors use induced currents to sense the presence of any metal—not just magnetic materials such as iron. A metal detector, shown in Figure P25.76, consists of two coils: a transmitter coil and a receiver coil. A high-frequency oscillating current in the transmitter coil generates an oscillating magnetic field along the axis and a changing flux through the receiver coil. Consequently, there is an oscillating induced current in the receiver coil.

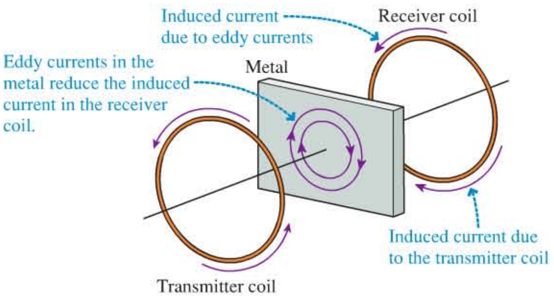


FIGURE P25.76

If a piece of metal is placed between the transmitter and the receiver, the oscillating magnetic field in the metal induces eddy currents in a plane parallel to the transmitter and receiver coils. The receiver coil then responds to the superposition of the transmitter's magnetic field and the magnetic field of the eddy currents. Because the eddy currents attempt to prevent the flux from changing, in accordance with Lenz's law, the net field at the receiver decreases when a piece of metal is inserted between the coils. Electronic circuits detect the current decrease in the receiver coil and set off an alarm.

76. | The metal detector will not detect insulators because
   A. Insulators block magnetic fields.
   B. No eddy current can be produced in an insulator.
   C. No emf can be produced in an insulator.
   D. An insulator will increase the field at the receiver.

77. | A metal detector can detect the presence of metal screws used to repair a broken bone inside the body. This tells us that
   A. The screws are made of magnetic materials.
   B. The tissues of the body are conducting.
   C. The magnetic fields of the device can penetrate the tissues of the body.
   D. The screws must be perfectly aligned with the axis of the device.

78. | Suppose the magnetic field from the transmitter coil in Figure P25.76 points toward the receiver coil and is increasing with time. As viewed along this axis, the induced currents are
   A. Clockwise in the metal, clockwise in the receiver coil
   B. Clockwise in the metal, counterclockwise in the receiver coil
   C. Counterclockwise in the metal, clockwise in the receiver coil
   D. Counterclockwise in the metal, counterclockwise in the receiver coil

79. | Which of the following changes would *not* produce a larger eddy current in the metal?
   A. Increasing the frequency of the oscillating current in the transmitter coil
   B. Increasing the magnitude of the oscillating current in the transmitter coil
   C. Increasing the resistivity of the metal
   D. Decreasing the distance between the metal and the transmitter

STOP TO THINK ANSWERS

Stop to Think 25.1: E. According to the right-hand rule, the magnetic force on a positive charge carrier is to the right.

Stop to Think 25.2: D. The field of the bar magnet emerges from the north pole and points upward. As the coil moves toward the pole, the flux through it is upward and increasing. To oppose the increase, the induced field must point downward. This requires a clockwise (negative) current. As the coil moves away from the pole, the upward flux is decreasing. To oppose the decrease, the induced field must point upward. This requires a counterclockwise (positive) current.

Stop to Think 25.3: E. The right-hand rule requires $\vec{B}$ to point into the page if the wave is to propagate upward.

Stop to Think 25.4: $I_D > I_A > I_B = I_C$. The intensity depends upon $\cos^2\theta$, where θ is the angle *between* the axes of the two filters. The filters in D have $\theta = 0°$, so all light is transmitted. The two filters in both B and C are crossed ($\theta = 90°$) and transmit no light at all.

Stop to Think 25.5: A. The photon energy is proportional to the frequency. The photons of the 90.5 MHz station each have lower energy, so more photons must be emitted per second.

Stop to Think 25.6: D. A hotter object emits more radiation across the *entire* spectrum than a cooler object. The 6000 K star has its maximum intensity in the blue region of the spectrum, but it still emits more red radiation than the somewhat cooler stars.