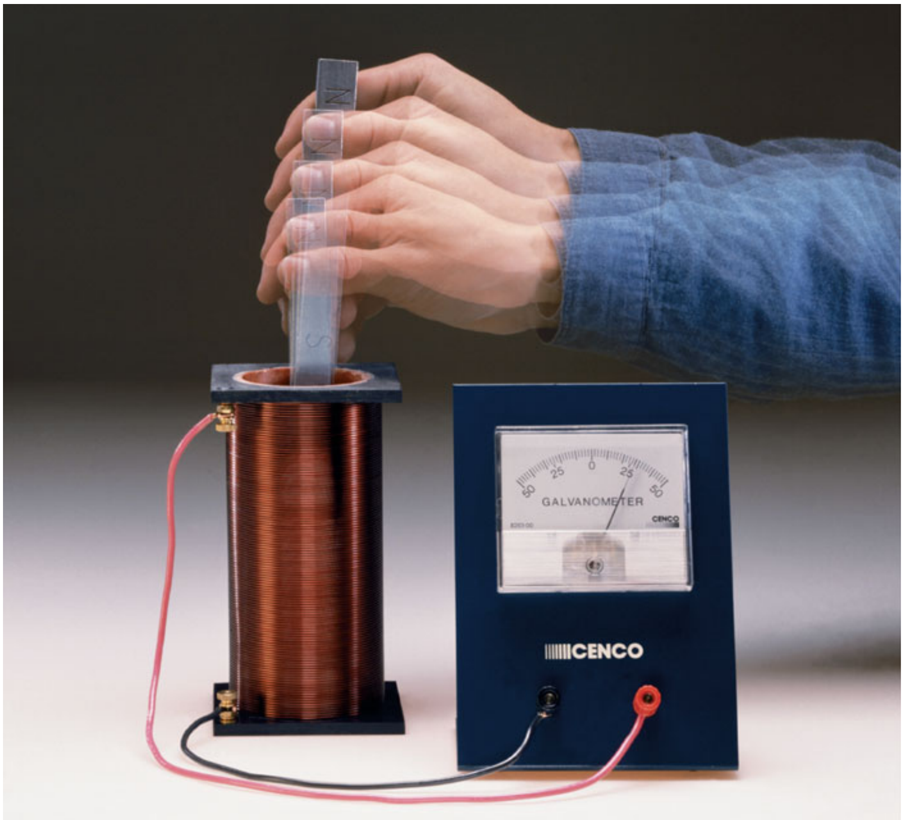
One of the great laws of physics is Faraday's law of induction, which says that a changing magnetic flux produces an induced emf. This photo shows a bar magnet moving into (or out of) a coil of wire, and the galvanometer registers an induced current. This phenomenon of electromagnetic induction is the basis for many practical devices, including generators, alternators, transformers, magnetic recording on tape or disk (hard drive), and computer memory.



CHAPTER 21

Electromagnetic Induction and Faraday's Law

CONTENTS

CHAPTER-OPENING QUESTION—Guess now!

In the photograph above, the bar magnet is inserted down into the coil of wire, and is left there for 1 minute; then it is pulled up and out from the coil. What would an observer watching the galvanometer see?

(a) No change (pointer stays on zero): without a battery there is no current to detect.
(b) A small current flows while the magnet is inside the coil of wire.
(c) A current spike as the magnet enters the coil, and then nothing.
(d) A current spike as the magnet enters the coil, and then a steady small current.
(e) A current spike as the magnet enters the coil, then nothing (pointer at zero), then a current spike in the opposite direction as the magnet exits the coil.

In Chapter 20, we discussed two ways in which electricity and magnetism are related: (1) an electric current produces a magnetic field; and (2) a magnetic field exerts a force on an electric current or on a moving electric charge. These discoveries were made in 1820–1821. Scientists then began to wonder: if electric currents produce a magnetic field, is it possible that a magnetic field can produce an electric current? Ten years later the American Joseph Henry (1797–1878) and the Englishman Michael Faraday (1791–1867) independently found that it was possible. Henry actually made the discovery first. But Faraday published his results earlier and investigated the subject in more detail. We now discuss this phenomenon and some of its world-changing applications including the electric generator.

21–1 Induced EMF

In his attempt to produce an electric current from a magnetic field, Faraday used an apparatus like that shown in Fig. 21–1. A coil of wire, X, was connected to a battery. The current that flowed through X produced a magnetic field that was intensified by the ring-shaped iron core around which the wire was wrapped. Faraday hoped that a strong steady current in X would produce a great enough magnetic field to produce a current in a second coil Y wrapped on the same iron ring.

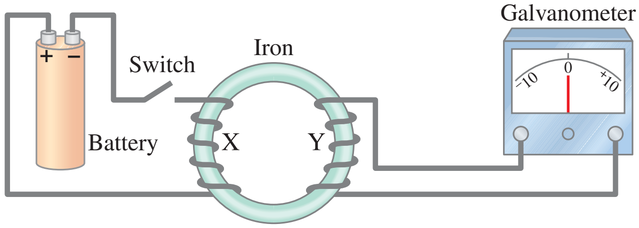


FIGURE 21–1 Faraday's experiment to induce an emf.

This second circuit, Y, contained a galvanometer to detect any current but contained no battery. He met no success with constant currents. But the long-sought effect was finally observed when Faraday noticed the galvanometer in circuit Y deflect strongly at the moment he closed the switch in circuit X. And the galvanometer deflected strongly in the opposite direction when he opened the switch in X. A constant current in X produced a constant magnetic field which produced *no* current in Y. Only when the current in X was starting or stopping was a current produced in Y.

Faraday concluded that although a constant magnetic field produces no current in a conductor, a *changing* magnetic field can produce an electric current. Such a current is called an **induced current**. When the magnetic field through coil Y changes, a current occurs in Y as if there were a source of emf in circuit Y. We therefore say that

a changing magnetic field induces an emf.

CAUTION

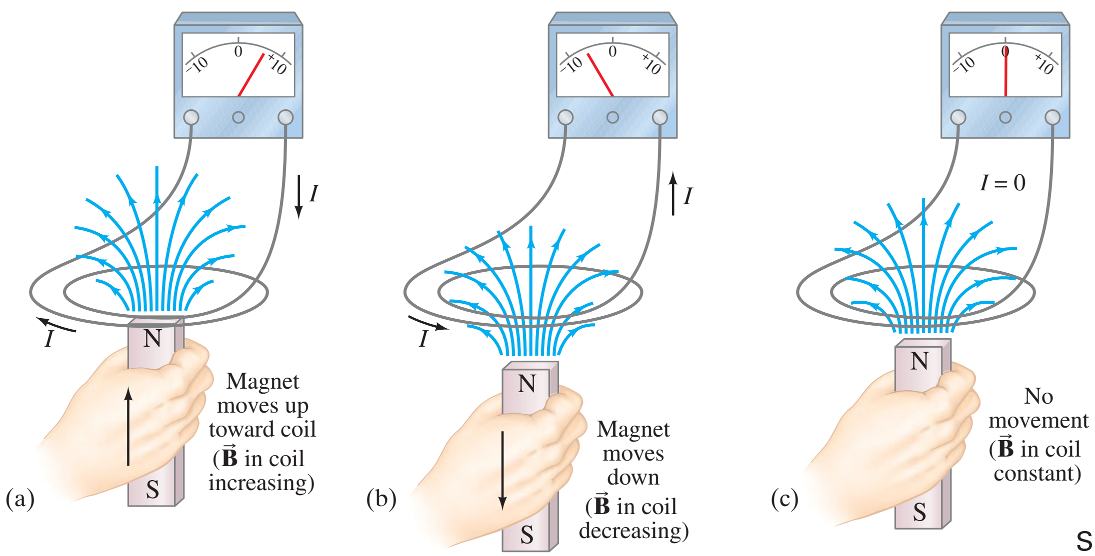
Changing $\vec{\mathbf{B}}$, not $\vec{\mathbf{B}}$ itself, induces current

Faraday did further experiments on **electromagnetic induction**, as this phenomenon is called. For example, Fig. 21–2 shows that if a magnet is moved quickly into a coil of wire, a current is induced in the wire. If the magnet is quickly removed, a current is induced in the opposite direction ($\vec{\mathbf{B}}$ through the coil decreases). Furthermore, if the magnet is held steady and the coil of wire is moved toward or away from the magnet, again an emf is induced and a current flows. Motion or change is required to induce an emf. It doesn't matter whether the magnet or the coil moves. It is their *relative motion* that counts.

CAUTION

Relative motion—magnet or coil moving induces current

FIGURE 21–2 (a) A current is induced when a magnet is moved toward a coil, momentarily increasing the magnetic field through the coil. (b) The induced current is opposite when the magnet is moved away from the coil ($\vec{\mathbf{B}}$ decreases). Note that the galvanometer zero is at the center of the scale and the needle deflects left or right, depending on the direction of the current. In (c), no current is induced if the magnet does not move relative to the coil. It is the relative motion that counts here: the magnet can be held steady and the coil moved, which also induces an emf.



EXERCISE A Return to the Chapter-Opening Question, page 590, and answer it again now. Try to explain why you may have answered differently the first time.

21–2 Faraday's Law of Induction; Lenz's Law

Faraday investigated quantitatively what factors influence the magnitude of the emf induced. He found first of all that the more rapidly the magnetic field changes, the greater the induced emf. He also found that the induced emf depends on the area of the circuit loop (and also the angle it makes with $\vec{\mathbf{B}}$). In fact, it is found that the emf is proportional to the rate of change of the **magnetic flux**, Φ_B, passing through the circuit or loop of area A. Magnetic flux for a uniform magnetic field through a loop of area A is defined as

$$\Phi_B = B_\perp A = BA\cos\theta. \qquad [B \text{ uniform}] \quad \textbf{(21–1)}$$

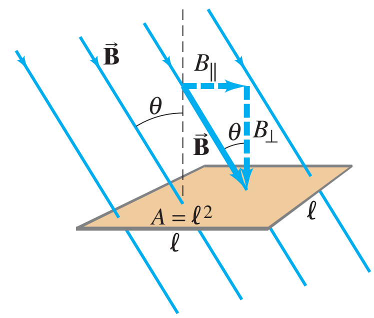


FIGURE 21–3 Determining the flux through a flat loop of wire. This loop is square, of side ℓ and area $A = \ell^2$.

Here $B_\perp$ is the component of the magnetic field $\vec{\mathbf{B}}$ perpendicular to the face of the loop, and θ is the angle between $\vec{\mathbf{B}}$ and a line perpendicular to the face of the loop. These quantities are shown in Fig. 21–3 for a square loop of side ℓ whose area is $A = \ell^2$. When the face of the loop is parallel to $\vec{\mathbf{B}}$, $\theta = 90°$ and $\Phi_B = 0$. When $\vec{\mathbf{B}}$ is perpendicular to the face of the loop, $\theta = 0°$, and

$$\Phi_B = BA. \qquad [\text{uniform } \vec{\mathbf{B}} \perp \text{loop face}]$$

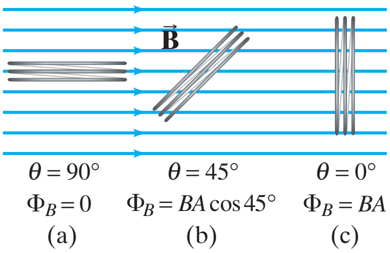


FIGURE 21–4 Magnetic flux Φ_B is proportional to the number of lines of $\vec{\mathbf{B}}$ that pass through the loops of a coil (here with 3 loops).

As we saw in Chapter 20, the lines of $\vec{\mathbf{B}}$ (like lines of $\vec{\mathbf{E}}$) can be drawn such that the number of lines per unit area is proportional to the field strength. Then the flux Φ_B can be thought of as being proportional to the *total number of lines passing through the area enclosed by the loop*. This is illustrated in Fig. 21–4, where three wire loops of a coil are viewed from the side (on edge). For $\theta = 90°$, no magnetic field lines pass through the loops and $\Phi_B = 0$, whereas Φ_B is a maximum when $\theta = 0°$. The unit of magnetic flux is the tesla-meter^2; this is called a **weber**: $1\text{ Wb} = 1\text{ T}\cdot\text{m}^2$.

With our definition of flux, Eq. 21–1, we can write down the results of Faraday's investigations: The emf $\mathscr{E}$ induced in a circuit is equal to the rate of change of magnetic flux through the circuit:

FARADAY'S LAW OF INDUCTION

$$\mathscr{E} = -\frac{\Delta\Phi_B}{\Delta t}. \qquad [1 \text{ loop}] \quad \textbf{(21–2a)}$$

This fundamental result is known as **Faraday's law of induction**, and it is one of the basic laws of electromagnetism.

If the circuit contains N loops that are closely wrapped so the same flux passes through each, the emfs induced in each loop add together, so the total emf is

FARADAY'S LAW OF INDUCTION

$$\mathscr{E} = -N\frac{\Delta\Phi_B}{\Delta t}. \qquad [N \text{ loops}] \quad \textbf{(21–2b)}$$

EXAMPLE 21–1 A loop of wire in a magnetic field. A square loop of wire of side $\ell = 5.0\text{ cm}$ is in a uniform magnetic field $B = 0.16\text{ T}$. What is the magnetic flux in the loop (*a*) when $\vec{\mathbf{B}}$ is perpendicular to the face of the loop and (*b*) when $\vec{\mathbf{B}}$ is at an angle of 30° to the area of the loop? (*c*) What is the magnitude of the average current in the loop if it has a resistance of 0.012 Ω and it is rotated from position (*b*) to position (*a*) in 0.14 s?

APPROACH We use the definition $\Phi_B = BA\cos\theta$, Eq. 21–1, to calculate the magnetic flux. Then we use Faraday's law of induction to find the induced emf in the coil, and from that the induced current ($I = \mathscr{E}/R$).

SOLUTION The area of the coil is $A = \ell^2 = (5.0\times10^{-2}\text{ m})^2 = 2.5\times10^{-3}\text{ m}^2$. (*a*) $\vec{\mathbf{B}}$ is perpendicular to the coil's face, so $\theta = 0°$ and

$$\Phi_B = BA\cos 0° = (0.16\text{ T})(2.5\times10^{-3}\text{ m}^2)(1) = 4.0\times10^{-4}\text{ T}\cdot\text{m}^2$$

or 4.0×10^{-4} Wb.

(*b*) The angle θ is 30° and $\cos 30° = 0.866$, so

$$\Phi_B = BA\cos\theta = (0.16\text{ T})(2.5\times10^{-3}\text{ m}^2)\cos 30° = 3.5\times10^{-4}\text{ T}\cdot\text{m}^2$$

or 3.5×10^{-4} Wb, a bit less than in part (*a*).

(*c*) The magnitude of the induced emf (Eq. 21–2a) during the 0.14-s time interval is

$$\mathscr{E} = \frac{\Delta\Phi_B}{\Delta t} = \frac{(4.0 \times 10^{-4}\,\mathrm{T \cdot m^2}) - (3.5 \times 10^{-4}\,\mathrm{T \cdot m^2})}{0.14\,\mathrm{s}} = 3.6 \times 10^{-4}\,\mathrm{V}.$$

Before and after the loop rotates, when it is at rest, the emf is zero. The current in the wire loop (Ohm's law) while it is rotating is

$$I = \frac{\mathscr{E}}{R} = \frac{3.6 \times 10^{-4}\,\mathrm{V}}{0.012\,\Omega} = 0.030\,\mathrm{A} = 30\,\mathrm{mA}.$$

The minus signs in Eqs. 21–2a and b are there to remind us in which direction the induced emf acts. Experiments show that

a current produced by an induced emf moves in a direction so that the magnetic field created by that current opposes the original change in flux.

This is known as **Lenz's law**. Be aware that we are now discussing two distinct magnetic fields: (1) the changing magnetic field or flux that induces the current, and (2) the magnetic field produced by the induced current (all currents produce a magnetic field). The second (induced) field opposes the *change* in the first.

CAUTION
Distinguish two different magnetic fields

Lenz's law can be said another way, valid even if no current can flow (as when a circuit is not complete):

An induced emf is always in a direction that opposes the original change in flux that caused it.

Let us apply Lenz's law to the relative motion between a magnet and a coil, Fig. 21–2. The changing flux through the coil induces an emf in the coil, producing a current. This induced current produces its own magnetic field. In Fig. 21–2a the distance between the coil and the magnet decreases. The magnet's magnetic field (and number of field lines) through the coil increases, and therefore the flux increases. The magnetic field of the magnet points upward. To oppose the upward increase, the magnetic field produced by the induced current needs to point *downward* inside the coil. Thus, Lenz's law tells us the current moves as shown in Fig. 21–2a (use the right-hand rule). In Fig. 21–2b, the flux *decreases* (because the magnet is moved away and B decreases), so the induced current in the coil produces an *upward* magnetic field through the coil that is "trying" to maintain the status quo. Thus the current in Fig. 21–2b is in the opposite direction from Fig. 21–2a.

It is important to note that an emf is induced whenever there is a change in *flux* through the coil, and we now consider some more possibilities.

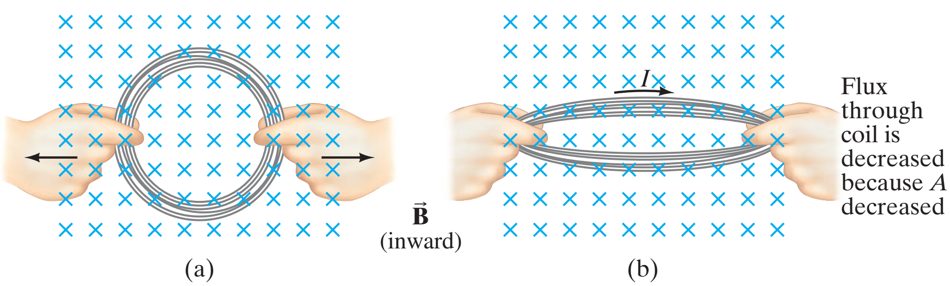


FIGURE 21–5 A current can be induced by changing the coil's area, even though B doesn't change. Here the area A is reduced by pulling on the sides of the coil: the *flux* through the coil is reduced as we go from (a) to (b). The brief induced current acts in the direction shown so as to try to maintain the original flux ($\Phi = BA$) by producing its own magnetic field into the page. That is, as area A decreases, the current acts to increase B in the original (inward) direction.

Magnetic flux $\Phi_B = BA\cos\theta$, so an emf can be induced in three ways: (1) by a changing magnetic field B; (2) by changing the area A of the loop in the field; or (3) by changing the loop's orientation θ with respect to the field. Figures 21–1 and 21–2 showed case 1. Cases 2 and 3 are illustrated in Figs. 21–5 and 21–6.

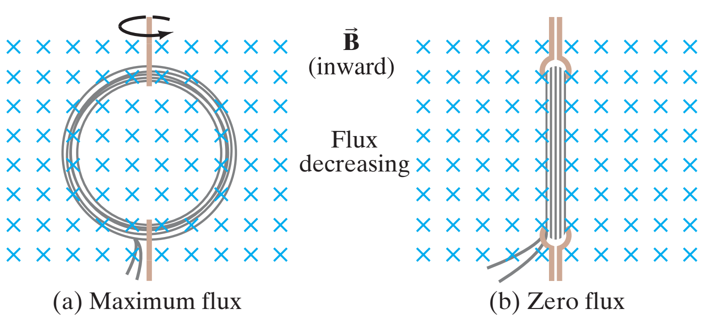


FIGURE 21–6 A current can be induced by rotating a coil in a magnetic field. The flux through the coil changes from (a) to (b) because θ (in Eq. 21–1, $\Phi = BA\cos\theta$) went from 0° ($\cos\theta = 1$) to 90° ($\cos\theta = 0$).

FIGURE 21–7 Example 21–2: An induction stove.

CONCEPTUAL EXAMPLE 21–2 **Induction stove.** In an induction stove (Fig. 21–7), an ac current exists in a coil that is the "burner" (a burner that never gets hot). Why will it heat a metal pan, usually iron, but not a glass container?

RESPONSE The ac current sets up a changing magnetic field that passes through the pan bottom. This changing magnetic field induces a current in the pan, and since the pan offers resistance, electric energy is transformed to thermal energy which heats the pan and its contents. If the pan is iron, magnetic hysteresis due to the changing current produces additional heating. A glass container offers such high resistance that little current is induced and little energy is transferred $(P = V^2/R)$.

PROBLEM SOLVING

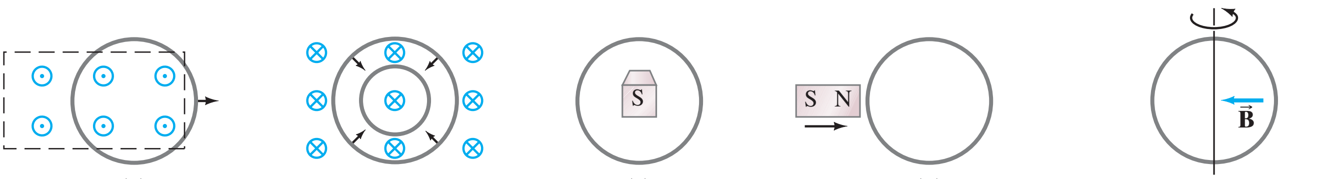
Lenz's Law

Lenz's law is used to determine the direction of the (conventional) electric current induced in a loop due to a change in magnetic flux inside the loop. To produce an induced current you need

(a) a closed conducting loop, and

(b) an external magnetic flux through the loop that is changing in time.

1. Determine whether the magnetic flux ($\Phi_B = BA\cos\theta$) inside the loop is decreasing, increasing, or unchanged.
2. The magnetic field due to the induced current: (a) points in the same direction as the external field if the flux is decreasing; (b) points in the opposite direction from the external field if the flux is increasing; or (c) is zero if the flux is not changing.
3. Once you know the direction of the induced magnetic field, use right-hand-rule-1 (page 563, Chapter 20) to find the direction of the induced current.
4. Always keep in mind that there are two magnetic fields: (1) an external field whose flux must be changing if it is to induce an electric current, and (2) a magnetic field produced by the induced current.



(a) Pulling a round loop to the right out of a magnetic field which points out of the page

(b) Shrinking a loop in a magnetic field pointing into the page

(c) S magnetic pole moving from below, up toward the loop

(d) N magnetic pole moving toward loop in the plane of the loop

(e) Rotating the loop by pulling the left side toward us and pushing the right side in; the magnetic field points from right to left

FIGURE 21–8 Example 21–3.

CONCEPTUAL EXAMPLE 21–3 **Practice with Lenz's law.** In which direction is the current, induced in the circular loop for each situation in Fig. 21–8?

RESPONSE In (*a*), the magnetic field initially pointing out of the page passes through the loop. If you pull the loop out of the field, magnetic flux through the loop decreases; so the induced current will be in a direction to maintain the decreasing flux through the loop: the current will be counterclockwise to produce a magnetic field outward (toward the reader).

(*b*) The external field is into the page. The coil area gets smaller, so the flux will decrease; hence the induced current will be clockwise, producing its own field into the page to make up for the flux decrease.

(*c*) Magnetic field lines point into the S pole of a magnet, so as the magnet moves toward us and the loop, the magnet's field points into the page and is getting stronger. The current in the loop will be induced in the counterclockwise direction in order to produce a field $\vec{\mathbf{B}}$ *out* of the page.

(*d*) The field is in the plane of the loop, so no magnetic field lines pass through the loop and the flux through the loop is zero throughout the process; hence there is no change in flux and no induced emf or current in the loop.

(*e*) Initially there is no flux through the loop. When you start to rotate the loop, the external field through the loop begins increasing to the left. To counteract this change in flux, the loop will have current induced in a counterclockwise direction so as to produce its own field to the right.

CAUTION

Magnetic field created by induced current opposes change in external flux, not necessarily opposing the external field

EXAMPLE 21–4 **Pulling a coil from a magnetic field.** A 100-loop square coil of wire, with side $\ell = 5.00$ cm and total resistance $R = 100\,\Omega$, is positioned perpendicular to a uniform magnetic field $B = 0.600$ T, as shown in Fig. 21–9. It is quickly pulled from the field at constant speed (moving perpendicular to $\vec{\mathbf{B}}$) to a region where B drops abruptly to zero. At $t = 0$, the right edge of the coil is at the edge of the field. It takes 0.100 s for the whole coil to reach the field-free region. Determine (*a*) the rate of change in flux through one loop of the coil, and (*b*) the total emf and current induced in the 100-loop coil. (*c*) How much energy is dissipated in the coil? (*d*) What was the average force required (F_{ext})?

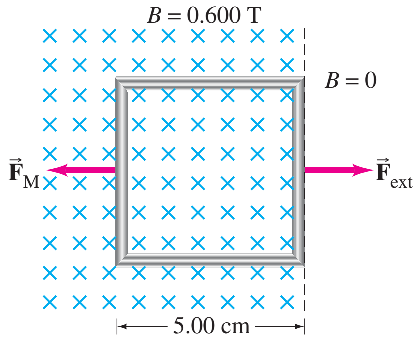


FIGURE 21–9 Example 21–4. The square coil in a magnetic field $B = 0.600$ T is pulled abruptly to the right to a region where $B = 0$. (The forces shown are discussed in the alternate solution at the end of Example 21–4.)

APPROACH We start by finding how the magnetic flux, $\Phi_B = BA\cos 0° = BA$, changes during the time interval $\Delta t = 0.100$ s. Faraday's law then gives the induced emf and Ohm's law gives the current.

SOLUTION (*a*) The coil's area is $A = \ell^2 = \left(5.00 \times 10^{-2}\,\text{m}\right)^2 = 2.50 \times 10^{-3}\,\text{m}^2$. The flux through one loop is initially $\Phi_B = BA = (0.600\,\text{T})\left(2.50 \times 10^{-3}\,\text{m}^2\right) = 1.50 \times 10^{-3}$ Wb. After 0.100 s, the flux is zero. The rate of change in flux is constant (because the coil is square), and for one loop is equal to

$$\frac{\Delta\Phi_B}{\Delta t} = \frac{0 - \left(1.50 \times 10^{-3}\,\text{Wb}\right)}{0.100\,\text{s}} = -1.50 \times 10^{-2}\,\text{Wb/s}.$$

(*b*) The emf induced (Eq. 21–2) in the 100-loop coil during this 0.100-s interval is

$$\mathscr{E} = -N\frac{\Delta\Phi_B}{\Delta t} = -(100)\left(-1.50 \times 10^{-2}\,\text{Wb/s}\right) = 1.50\,\text{V}.$$

The current is found by applying Ohm's law to the 100-Ω coil:

$$I = \frac{\mathscr{E}}{R} = \frac{1.50\,\text{V}}{100\,\Omega} = 1.50 \times 10^{-2}\,\text{A} = 15.0\,\text{mA}.$$

By Lenz's law, the current must be clockwise to produce more $\vec{\mathbf{B}}$ into the page and thus oppose the decreasing flux into the page.

(*c*) The total energy dissipated in the coil is the product of the power $\left(= I^2R\right)$ and the time:

$$E = Pt = I^2Rt = \left(1.50 \times 10^{-2}\,\text{A}\right)^2(100\,\Omega)(0.100\,\text{s}) = 2.25 \times 10^{-3}\,\text{J}.$$

(*d*) We can use the result of part (*c*) and apply the work-energy principle: the energy dissipated E is equal to the work W needed to pull the coil out of the field (Chapter 6). Because $W = \bar{F}_{\text{ext}}\,d$ where $d = 5.00$ cm, then

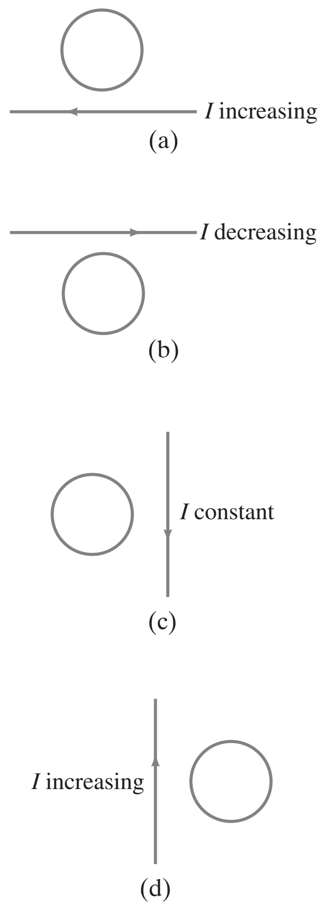
$$\bar{F}_{\text{ext}} = \frac{W}{d} = \frac{2.25 \times 10^{-3}\,\text{J}}{5.00 \times 10^{-2}\,\text{m}} = 0.0450\,\text{N}.$$

Alternate Solution (*d*) We can also calculate the force directly using Eq. 20–2 for constant $\vec{\mathbf{B}}$, $F = I\ell B$. The force the magnetic field exerts on the top and bottom sections of the square coil of Fig. 21–9 are in opposite directions and cancel each other. The magnetic force $\vec{\mathbf{F}}_{\text{M}}$ exerted on the left vertical section of the square coil acts to the left as shown because the current is up (clockwise). The right side of the loop is in the region where $\vec{\mathbf{B}} = 0$. Hence the external force to the right, $\vec{\mathbf{F}}_{\text{ext}}$, needed to just overcome the magnetic force to the left (on $N = 100$ loops), is

$$F_{\text{ext}} = NI\ell B = (100)(0.0150\,\text{A})(0.0500\,\text{m})(0.600\,\text{T}) = 0.0450\,\text{N},$$

which is the same answer, confirming our use of energy conservation above.

FIGURE 21–10 Exercise B.



EXERCISE B What is the direction of the induced current in the circular loop due to the current shown in each part of Fig. 21–10?

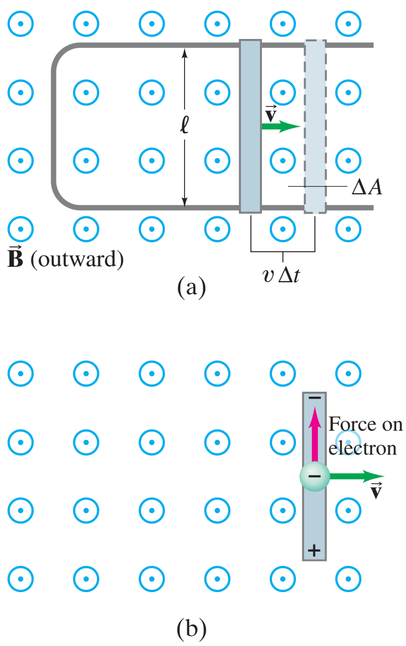


FIGURE 21–11 (a) A conducting rod is moved to the right on a U-shaped conductor in a uniform magnetic field $\vec{\mathbf{B}}$ that points out of the page. The induced current is clockwise. (b) Upward force on an electron in the metal rod (moving to the right) due to $\vec{\mathbf{B}}$ pointing out of the page; hence electrons can collect at the top of the rod, leaving + charge at the bottom.

21–3 EMF Induced in a Moving Conductor

Another way to induce an emf is shown in Fig. 21–11a, and this situation helps illuminate the nature of the induced emf. Assume that a uniform magnetic field $\vec{\mathbf{B}}$ is perpendicular to the area bounded by the U-shaped conductor and the movable rod resting on it. If the rod is made to move at a speed v to the right, it travels a distance $\Delta x = v\,\Delta t$ in a time Δt. Therefore, the area of the loop increases by an amount $\Delta A = \ell\,\Delta x = \ell v\,\Delta t$ in a time Δt. By Faraday's law there is an induced emf $\mathscr{E}$ whose magnitude is given by

$$\mathscr{E} = \frac{\Delta\Phi_B}{\Delta t} = \frac{B\,\Delta A}{\Delta t} = \frac{B\ell v\,\Delta t}{\Delta t} = B\ell v. \qquad \textbf{(21–3)}$$

The induced current is clockwise (to counter the increasing flux).

Equation 21–3 is valid as long as B, ℓ, and v are mutually perpendicular. (If they are not, we use only the components of each that are mutually perpendicular.) An emf induced on a conductor moving in a magnetic field is sometimes called **motional emf**.

We can also obtain Eq. 21–3 without using Faraday's law. We saw in Chapter 20 that a charged particle moving with speed v perpendicular to a magnetic field B experiences a force $F = qvB$ (Eq. 20–4). When the rod of Fig. 21–11a moves to the right with speed v, the electrons in the rod also move with this speed. Therefore, since $\vec{\mathbf{v}} \perp \vec{\mathbf{B}}$, each electron feels a force $F = qvB$, which acts up the page as the red arrow in Fig. 21–11b shows. If the rod is not in contact with the U-shaped conductor, electrons would collect at the upper end of the rod, leaving the lower end positive (see signs in Fig. 21–11b). There must thus be an induced emf. If the rod is in contact with the U-shaped conductor (Fig. 21–11a), the electrons will flow into the U. There will then be a clockwise (conventional) current in the loop. To calculate the emf, we determine the work W needed to move a charge q from one end of the rod to the other against this potential difference: W = force × distance = $(qvB)(\ell)$. The emf equals the work done per unit charge, so $\mathscr{E} = W/q = qvB\ell/q = B\ell v$, the same result as from Faraday's law above, Eq. 21–3.

EXERCISE C In what direction will the electrons flow in Fig. 21–11 if the rod moves to the left, decreasing the area of the current loop?

FIGURE 21–12 Example 21–5.

EXAMPLE 21–5 ESTIMATE Does a moving airplane develop a large emf? An airplane travels 1000 km/h in a region where the Earth's magnetic field is about 5×10^{-5} T and is nearly vertical (Fig. 21–12). What is the potential difference induced between the wing tips that are 70 m apart?

APPROACH We consider the wings to be a 70-m-long conductor moving through the Earth's magnetic field. We use Eq. 21–3 to get the emf.

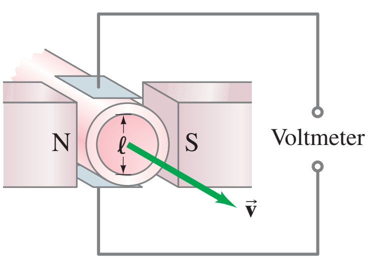
SOLUTION Since $v = 1000\text{ km/h} = 280\text{ m/s}$, and $\vec{\mathbf{v}} \perp \vec{\mathbf{B}}$, we have

$$\mathscr{E} = B\ell v = (5 \times 10^{-5}\,\text{T})(70\,\text{m})(280\,\text{m/s}) \approx 1\,\text{V}.$$

NOTE Not much to worry about.

PHYSICS APPLIED
Blood-flow measurement

FIGURE 21–13 Measurement of blood velocity from the induced emf. Example 21–6.



EXAMPLE 21–6 Electromagnetic blood-flow measurement. The rate of blood flow in our body's vessels can be measured using the apparatus shown in Fig. 21–13, since blood contains charged ions. Suppose that the blood vessel is 2.0 mm in diameter, the magnetic field is 0.080 T, and the measured emf is 0.10 mV. What is the flow velocity v of the blood?

APPROACH The magnetic field $\vec{\mathbf{B}}$ points horizontally from left to right (N pole toward S pole). The induced emf acts over the width $\ell = 2.0$ mm of the blood vessel, perpendicular to $\vec{\mathbf{B}}$ and $\vec{\mathbf{v}}$ (Fig. 21–13), just as in Fig. 21–11. We can then use Eq. 21–3 to get v.

SOLUTION We solve for v in Eq. 21–3:

$$v = \frac{\mathscr{E}}{B\ell} = \frac{(1.0 \times 10^{-4}\,\text{V})}{(0.080\,\text{T})(2.0 \times 10^{-3}\,\text{m})} = 0.63\,\text{m/s}.$$

NOTE In actual practice, an alternating current is used to produce an alternating magnetic field. The induced emf is then alternating.

21–4 Changing Magnetic Flux Produces an Electric Field

We have seen that a changing magnetic flux induces an emf. In a closed loop of wire there will also be an induced current, which implies there is an electric field in the wire causing the electrons to start moving. Indeed, this and other results suggest the important conclusion that

a changing magnetic flux produces an electric field.

This result applies not only to wires and other conductors, but is a general result that applies to any region in space. Indeed, an electric field will be produced (= induced) at any point in space where there is a changing magnetic field.

We can get a simple formula for E in terms of B for the case of electrons in a moving conductor, as in Fig. 21–11. The electrons feel a force (upwards in Fig. 21–11b); and if we put ourselves in the reference frame of the conductor, this force accelerating the electrons implies that there is an electric field in the conductor. Electric field is defined as the force per unit charge, $E = F/q$, where here $F = qvB$ (Eq. 20–4). Thus the effective field E in the rod must be

$$E = \frac{F}{q} = \frac{qvB}{q} = vB, \qquad \textbf{(21–4)}$$

which is a useful result.

21–5 Electric Generators

We discussed alternating currents (ac) briefly in Section 18–7. Now we examine how ac is generated: by an **electric generator** or **dynamo**. A generator transforms mechanical energy into electric energy, just the opposite of what a motor does (Section 20–10). A simplified diagram of an **ac generator** is shown in Fig. 21–14. A generator consists of many loops of wire (only one is shown) wound on an **armature** that can rotate in a magnetic field. The axle is turned by some mechanical means (falling water, steam turbine, car motor belt), and an emf is induced in the rotating coil. An electric current is thus the *output* of a generator. Suppose in Fig. 21–14 that the armature is rotating clockwise; then right-hand-rule-3 (p. 568) applied to charged particles in the wire (or Lenz's law) tells us that the (conventional) current in the wire labeled b on the armature is outward towards us; therefore the current is outward through brush b. (Each brush is fixed and presses against a continuous slip ring that rotates with the armature.) After one-half revolution, wire b will be where wire a is now in Fig. 21–14, and the current then at brush b will be inward. Thus the current produced is alternating.

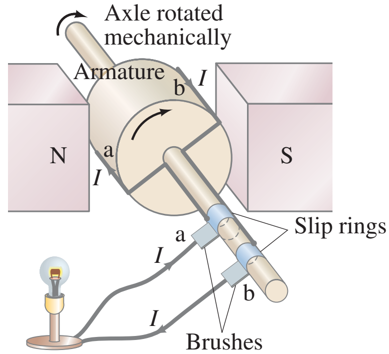
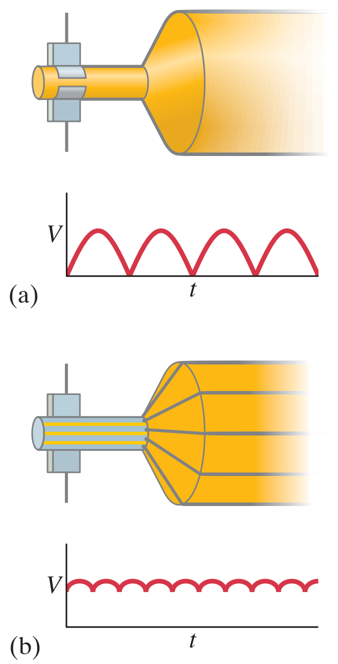


FIGURE 21–14 An ac generator.

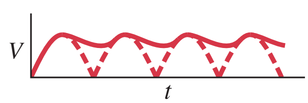
FIGURE 21–15 (a) A dc generator with one set of commutators, and (b) a dc generator with many sets of commutators and windings.



The frequency f is 60 Hz for general use in the United States and Canada, whereas 50 Hz is used in many countries. Most of the power generated in the United States is done at steam plants, where the burning of fossil fuels (coal, oil, natural gas) boils water to produce high-pressure steam that turns a turbine connected to the generator axle (Fig. 15–21). Turbines can also be turned by water pressure at a dam (hydroelectric). At nuclear power plants, the nuclear energy released is used to produce steam to turn turbines. Indeed, a heat engine (Chapter 15) connected to a generator is the principal means of generating electric power. The frequency of 60 Hz or 50 Hz is maintained very precisely by power companies.

A **dc generator** is much like an ac generator, except the slip rings are replaced by split-ring commutators, Fig. 21–15a, just as in a dc motor (Figs. 20–37 and 20–38). The output of such a generator is as shown and can be smoothed out by placing a capacitor in parallel with the output.† More common is the use of many armature windings, as in Fig. 21–15b, which produces a smoother output.

†A capacitor tends to store charge and, if the time constant RC is long enough, helps to smooth out the voltage as shown in the figure to the right.



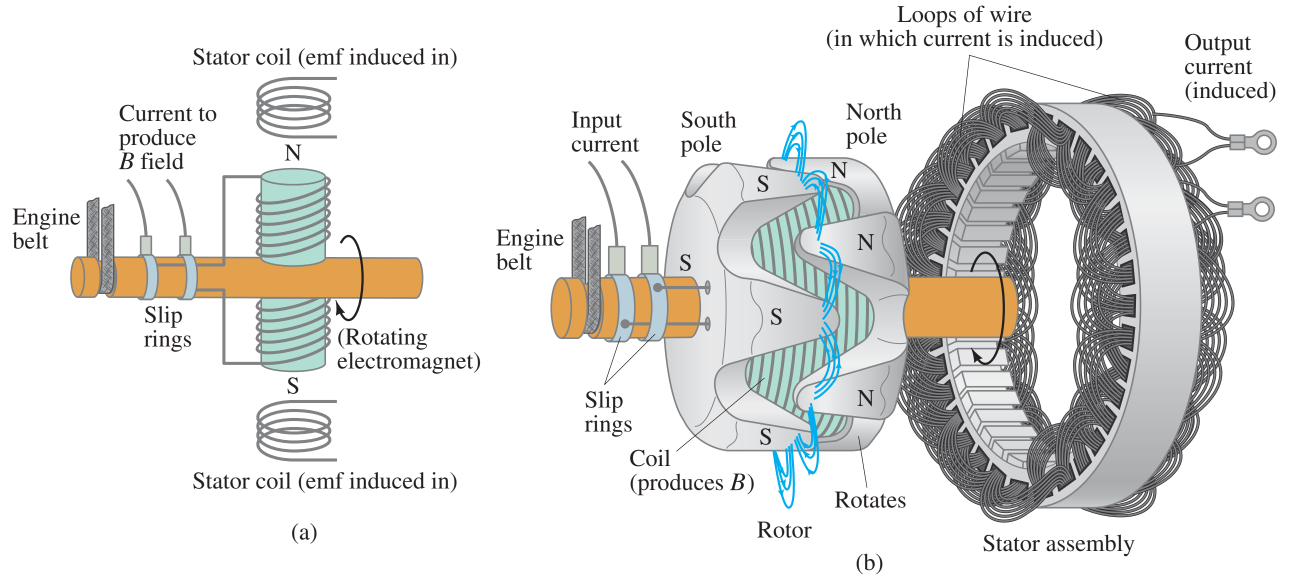


FIGURE 21–16 (a) Simplified schematic diagram of an alternator. The input current to the rotor from the battery is connected through continuous slip rings. Sometimes the rotor electromagnet is replaced by a permanent magnet (no input current). (b) Actual shape of an alternator. The rotor is made to turn by a belt from the engine. The current in the wire coil of the rotor produces a magnetic field inside it on its axis that points horizontally from left to right (not shown), thus making north and south poles of the plates attached at either end. These end plates are made with triangular fingers that are bent over the coil—hence there are alternating N and S poles quite close to one another, with magnetic field lines between them as shown by the blue lines. As the rotor turns, these field lines pass through the fixed stator coils (shown on the right for clarity, but in operation the rotor rotates within the stator), inducing a current in them, which is the output.

* Alternators

PHYSICS APPLIED
Alternators

Automobiles used to use dc generators. Today they mainly use **alternators**, which avoid the problems of wear and electrical arcing (sparks) across the split-ring commutators of dc generators. Alternators differ from generators in that an electromagnet, called the **rotor**, is fed by current from the battery and is made to rotate by a belt from the engine. The magnetic field of the turning rotor passes through a surrounding set of stationary coils called the **stator** (Fig. 21–16), inducing an alternating current in the stator coils, which is the output. This ac output is changed to dc for charging the battery by the use of semiconductor diodes, which allow current flow in one direction only.

Deriving the Generator Equation

FIGURE 21–17 The emf is induced in the segments ab and cd, whose velocity components perpendicular to the field $\vec{\mathbf{B}}$ are $v \sin\theta$.

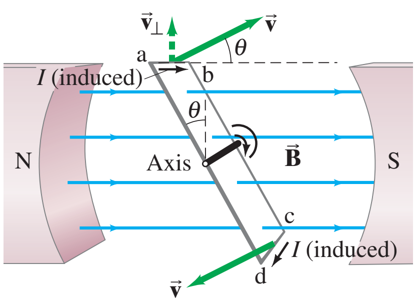


Figure 21–17 shows the wire loop on a generator armature. The loop is being made to rotate clockwise in a uniform magnetic field $\vec{\mathbf{B}}$. The velocity of the two lengths ab and cd at this instant are shown. Although the sections of wire bc and da are moving, the force on electrons in these sections is toward the side of the wire, not along the wire's length. The emf generated is thus due only to the force on charges in the sections ab and cd. From right-hand-rule-3, we see that the direction of the induced current in ab is from a toward b. And in the lower section, it is from c to d; so the flow is continuous in the loop. The magnitude of the emf generated in ab is given by Eq. 21–3, except that we must take the component of the velocity perpendicular to B:

$$\mathscr{E} = B\ell v_{\perp},$$

where ℓ is the length of ab. From Fig. 21–17 we see that $v_{\perp} = v \sin\theta$, where θ is the angle the loop's face makes with the vertical. The emf induced in cd has the same magnitude and is in the same direction. Therefore their emfs add, and the total emf is

$$\mathscr{E} = 2NB\ell v \sin\theta,$$

where we have multiplied by N, the number of loops in the coil.

If the coil is rotating with constant angular velocity ω, then the angle $\theta = \omega t$. From the angular equations (Eq. 8–4), $v = \omega r = \omega(h/2)$, where r is the distance from the rotation axis and h is the length of bc or ad. Thus $\mathscr{E} = 2NB\omega\ell(h/2) \sin\omega t$, or

$$\mathscr{E} = NB\omega A \sin\omega t, \qquad \textbf{(21–5)}$$

where $A = \ell h$ is the area of the loop. This equation holds for any shape coil, not just for a rectangle as derived. Thus, the output emf of the generator is sinusoidally alternating (see Fig. 21–18 and Section 18–7). Since ω is expressed in radians per second, we can write $\omega = 2\pi f$, where f is the frequency (in Hz = s^{-1}). The rms output (see Section 18–7, Eq. 18–8b) is

$$V_{rms} = \frac{NB\omega A}{\sqrt{2}}.$$

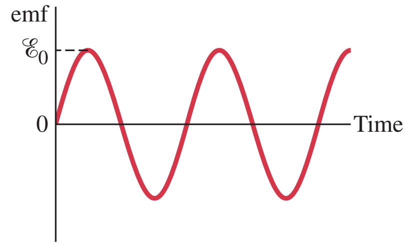


FIGURE 21–18 An ac generator produces an alternating current. The output emf $\mathscr{E} = \mathscr{E}_0 \sin \omega t$, where $\mathscr{E}_0 = NA\omega B$ (Eq. 21–5).

EXAMPLE 21–7 **An ac generator.** The armature of a 60-Hz ac generator rotates in a 0.15-T magnetic field. If the area of the coil is $2.0 \times 10^{-2}\,\mathrm{m}^2$, how many loops must the coil contain if the peak output is to be $\mathscr{E}_0 = 170$ V?

APPROACH From Eq. 21–5 we see that the maximum emf is $\mathscr{E}_0 = NBA\omega$.

SOLUTION We solve Eq. 21–5 for N with $\omega = 2\pi f = (6.28)(60\,\mathrm{s}^{-1}) = 377\,\mathrm{s}^{-1}$:

$$N = \frac{\mathscr{E}_0}{BA\omega} = \frac{170\text{ V}}{(0.15\text{ T})(2.0 \times 10^{-2}\,\mathrm{m}^2)(377\,\mathrm{s}^{-1})} = 150\text{ turns.}$$

21–6 Back EMF and Counter Torque; Eddy Currents

Back EMF, in a Motor

A motor turns and produces mechanical energy when a current is made to flow in it. From our description in Section 20–10 of a simple dc motor, you might expect that the armature would accelerate indefinitely due to the torque on it. However, as the armature of the motor turns, the magnetic flux through the coil changes and an emf is generated. This induced emf acts to oppose the motion (Lenz's law) and is called the **back emf** or **counter emf**. The greater the speed of the motor, the greater the back emf. A motor normally turns and does work on something, but if there were no load to push (or rotate), the motor's speed would increase until the back emf equaled the input voltage. When there is a mechanical load, the speed of the motor may be limited also by the load. The back emf will then be less than the external applied voltage. The greater the mechanical load, the slower the motor rotates and the lower is the back emf ($\mathscr{E} \propto \omega$, Eq. 21–5).

EXAMPLE 21–8 **Back emf in a motor.** The armature windings of a dc motor have a resistance of 5.0 Ω. The motor is connected to a 120-V line, and when the motor reaches full speed against its normal load, the back emf is 108 V. Calculate (*a*) the current into the motor when it is just starting up, and (*b*) the current when the motor reaches full speed.

APPROACH As the motor is just starting up, it is turning very slowly, so there is negligible back emf. The only voltage is the 120-V line. The current is given by Ohm's law with $R = 5.0\,\Omega$. At full speed, we must include as emfs both the 120-V applied emf and the opposing back emf.

SOLUTION (*a*) At start up, the current is controlled by the 120 V applied to the coil's 5.0-Ω resistance. By Ohm's law,

$$I = \frac{V}{R} = \frac{120\text{ V}}{5.0\,\Omega} = 24\text{ A}.$$

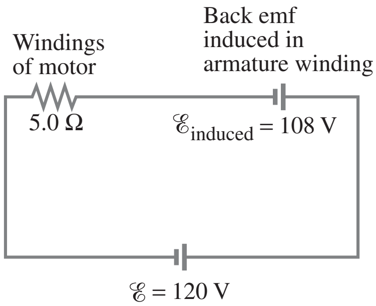
(*b*) When the motor is at full speed, the back emf must be included in the equivalent circuit shown in Fig. 21–19. In this case, Ohm's law (or Kirchhoff's rule) gives

$$120\text{ V} - 108\text{ V} = I(5.0\,\Omega).$$

Therefore

$$I = \frac{12\text{ V}}{5.0\,\Omega} = 2.4\text{ A}.$$

FIGURE 21–19 Circuit of a motor showing induced back emf. Example 21–8.



NOTE This result shows that the current can be very high when a motor first starts up. This is why the lights in your house may dim when the motor of the refrigerator (or other large motor) starts up. The large initial refrigerator current causes the voltage to the lights to drop because the house wiring has resistance and there is some voltage drop across it when large currents are drawn.

CONCEPTUAL EXAMPLE 21–9 **Motor overload.** When using an appliance such as a blender, electric drill, or sewing machine, if the appliance is overloaded or jammed so that the motor slows appreciably or stops while the power is still connected, the motor can burn out and be ruined. Explain why this happens.

PHYSICS APPLIED
Burning out a motor

RESPONSE The motors are designed to run at a certain speed for a given applied voltage, and the designer must take the expected back emf into account. If the rotation speed is reduced, the back emf will not be as high as expected ($\mathscr{E} \propto \omega$, Eq. 21–5). The current will increase and may become large enough that the windings of the motor heat up and may melt, ruining the motor.

Counter Torque, in a Generator

In a generator, the situation is the reverse of that for a motor. As we saw, the mechanical turning of the armature induces an emf in the loops, which is the output. If the generator rotates but is not connected to an external circuit, the emf exists at the terminals but there is no current. In this case, it takes little effort to turn the armature. But if the generator *is* connected to a device that draws current, then a current flows in the coils of the armature. Because this current-carrying coil is in an external magnetic field, there will be a torque exerted on it (as in a motor), and this torque opposes the motion (use right-hand-rule-2, page 568, for the force on a wire in Fig. 21–14 or 21–17). This is called a **counter torque**. The greater the electrical load—that is, the more current that is drawn—the greater will be the counter torque. Hence the external applied torque will have to be greater to keep the generator turning. This makes sense from the conservation of energy principle. More mechanical energy input is needed to produce more electric energy output.

EXERCISE D A bicycle headlight is powered by a generator that is turned by the bicycle wheel. (*a*) If you speed up, how does the power to the light change? (*b*) Does the generator resist being turned as the bicycle's speed increases, and if so how?

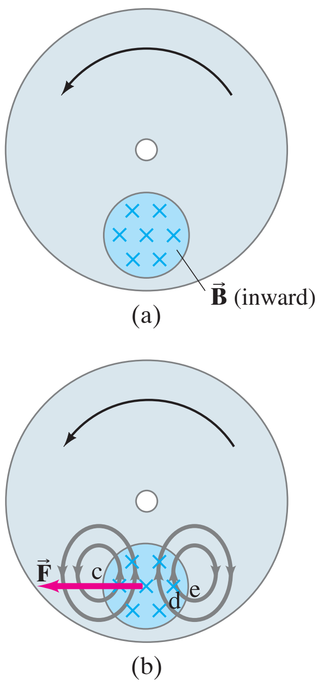


FIGURE 21–20 Production of eddy currents in a rotating wheel. The gray lines in (b) indicate induced current.

Eddy Currents

Induced currents are not always confined to well-defined paths such as in wires. Consider, for example, the rotating metal wheel in Fig. 21–20a. An external magnetic field is applied to a limited area of the wheel as shown and points into the page. The section of wheel in the magnetic field has an emf induced in it because the conductor is moving, carrying electrons with it. The flow of induced (conventional) current in the wheel is upward in the region of the magnetic field (Fig. 21–20b), and the current follows a downward return path outside that region. Why? According to Lenz's law, the induced currents oppose the change that causes them. Consider the part of the rotating wheel labeled c in Fig. 21–20b, where the magnetic field is zero but is just about to enter a region where $\vec{\mathbf{B}}$ points into the page. To oppose this inward increase in magnetic field, the induced current is counterclockwise to produce a field pointing out of the page (right-hand-rule-1). Similarly, region d is about to move to e, where $\vec{\mathbf{B}}$ is zero; hence the current is clockwise to produce an inward field opposed to this decreasing flux inward. These currents are referred to as **eddy currents**. They can be present in any conductor that is moving across a magnetic field or through which the magnetic flux is changing.

In Fig. 21–20b, the magnetic field exerts a force $\vec{\mathbf{F}}$ on the induced currents it has created, and that force opposes the rotational motion. Eddy currents can be used in this way as a smooth braking device on, say, a rapid-transit car. In order to stop the car, an electromagnet can be turned on that applies its field either to the wheels or to the moving steel rail below. Eddy currents can also be used to dampen (reduce) the oscillation of a vibrating system, which is referred to as **magnetic damping**.

Eddy currents, however, can be a problem. For example, eddy currents induced in the armature of a motor or generator produce heat ($P = I\mathscr{E}$) and waste energy. To reduce the eddy currents, the armatures are *laminated*; that is, they are made of very thin sheets of iron that are well insulated from one another (used also in transformers, Fig. 21–23). The total path length of the eddy currents is confined to each slab, which increases the total resistance; hence the current is less and there is less wasted energy.

Walk-through metal detectors (Fig. 21–21) use electromagnetic induction and eddy currents to detect metal objects. Several coils are situated in the walls of the walk-through at different heights. In one technique, the coils are given brief pulses of current, hundreds or thousands of times per second. When a person passes through the walk-through, any metal object being carried will have eddy currents induced in it, and the small magnetic field produced by that eddy current can be detected, setting off an alert or alarm.

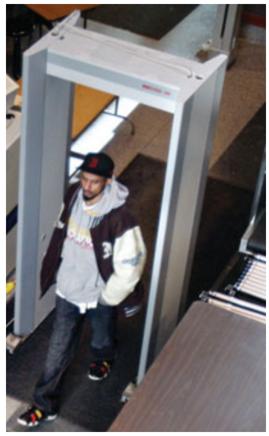


FIGURE 21–21 Metal detector.

PHYSICS APPLIED
Metal detector

21–7 Transformers and Transmission of Power

A transformer is a device for increasing or decreasing an ac voltage. Transformers are found everywhere: on utility poles (Fig. 21–22) to reduce the high voltage from the electric company to a usable voltage in houses (120 V or 240 V), in chargers for cell phones, laptops, and other electrical devices, in your car to give the needed high voltage to the spark plugs, and in many other applications. A **transformer** consists of two coils of wire known as the **primary** and **secondary** coils. The two coils can be interwoven (with insulated wire); or they can be linked by an iron core which is laminated to minimize eddy-current losses (Section 21–6), as shown in Fig. 21–23. Transformers are designed so that (nearly) all the magnetic flux produced by the current in the primary coil also passes through the secondary coil, and we assume this is true in what follows. We also assume that energy losses (in resistance and hysteresis) can be ignored—a good approximation for real transformers, which are often better than 99% efficient.

FIGURE 21–22 Repairing a step-down transformer on a utility pole.

When an ac voltage is applied to the primary coil, the changing magnetic field it produces will induce an ac voltage of the same frequency in the secondary coil. However, the voltage will be different according to the number of "turns" or loops in each coil. From Faraday's law, the voltage or emf induced in the secondary coil is

$$V_S = N_S \frac{\Delta\Phi_B}{\Delta t},$$

where N_S is the number of turns in the secondary coil, and $\Delta\Phi_B/\Delta t$ is the rate at which the magnetic flux changes.

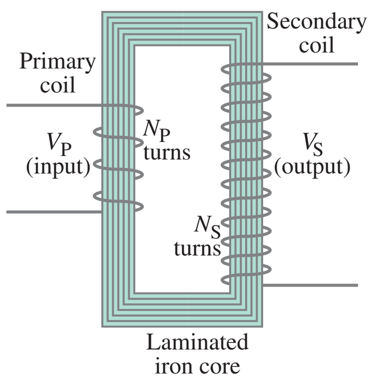
The input primary voltage, V_P, is related to the rate at which the flux changes through it,

$$V_P = N_P \frac{\Delta\Phi_B}{\Delta t},$$

where N_P is the number of turns in the primary coil. This follows because the changing flux produces a back emf, $N_P\,\Delta\Phi_B/\Delta t$, in the primary that balances the applied voltage V_P if the resistance of the primary can be ignored (Kirchhoff's rules). We divide these two equations, assuming little or no flux is lost, to find

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}. \qquad \textbf{(21–6)}$$

FIGURE 21–23 Step-up transformer ($N_P = 4$, $N_S = 12$).



This *transformer equation* tells how the secondary (output) voltage is related to the primary (input) voltage; V_S and V_P in Eq. 21–6 can be the rms values (Section 18–7) for both, or peak values for both. Steady dc voltages don't work in a transformer because there would be no changing magnetic flux.

If the secondary coil contains more loops than the primary coil $(N_S > N_P)$, we have a **step-up transformer**. The secondary voltage is greater than the primary voltage. For example, if the secondary coil has twice as many turns as the primary coil, then the secondary voltage will be twice that of the primary voltage. If N_S is less than N_P, we have a **step-down transformer**.

Although ac voltage can be increased (or decreased) with a transformer, we don't get something for nothing. Energy conservation tells us that the power output can be no greater than the power input. A well-designed transformer can be greater than 99% efficient, so little energy is lost to heat. The power output thus essentially equals the power input. Since power $P = IV$ (Eq. 18–5), we have

$$I_P V_P = I_S V_S,$$

or (remembering Eq. 21–6),

$$\frac{I_S}{I_P} = \frac{N_P}{N_S}. \tag{21–7}$$

EXAMPLE 21–10 Cell phone charger. The charger for a cell phone contains a transformer that reduces 120-V (or 240-V) ac to 5.0-V ac to charge the 3.7-V battery (Section 19–4). (It also contains diodes to change the 5.0-V ac to 5.0-V dc.) Suppose the secondary coil contains 30 turns and the charger supplies 700 mA. Calculate (*a*) the number of turns in the primary coil, (*b*) the current in the primary, and (*c*) the power transformed.

APPROACH We assume the transformer is ideal, with no flux loss, so we can use Eq. 21–6 and then Eq. 21–7.

SOLUTION (*a*) This is a step-down transformer, and from Eq. 21–6 we have

$$N_P = N_S \frac{V_P}{V_S} = \frac{(30)(120\text{ V})}{(5.0\text{ V})} = 720\text{ turns}.$$

(*b*) From Eq. 21–7

$$I_P = I_S \frac{N_S}{N_P} = (0.70\text{ A})\left(\frac{30}{720}\right) = 29\text{ mA}.$$

(*c*) The power transformed is

$$P = I_S V_S = (0.70\text{ A})(5.0\text{ V}) = 3.5\text{ W}.$$

NOTE The power in the primary coil, $P = (0.029\text{ A})(120\text{ V}) = 3.5\text{ W}$, is the same as the power in the secondary coil. There is 100% efficiency in power transfer for our ideal transformer.

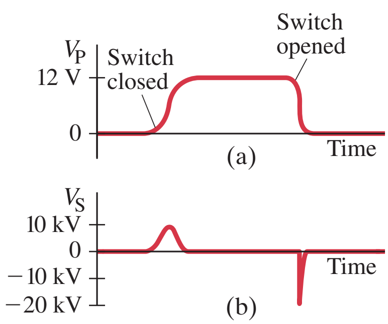


FIGURE 21–24 A dc voltage turned on and off as shown in (a) produces voltage pulses in the secondary (b). Voltage scales in (a) and (b) are not the same.

EXERCISE E How many turns would you want in the secondary coil of a transformer having $N_P = 400$ turns if it were to reduce the voltage from 120-V ac to 3.0-V ac?

PHYSICS APPLIED
Car ignition system

A transformer operates only on ac. A dc current in the primary coil does not produce a changing flux and therefore induces no emf in the secondary. However, if a dc voltage is applied to the primary through a switch, at the instant the switch is opened or closed there will be an induced voltage in the secondary. For example, if the dc is turned on and off as shown in Fig. 21–24a, the voltage induced in the secondary is as shown in Fig. 21–24b. Notice that the secondary voltage drops to zero when the dc voltage is steady. This is basically how, in the **ignition system** of an automobile, the high voltage is created to produce the spark across the gap of a spark plug that ignites the gas-air mixture. The transformer is referred to as an "ignition coil," and transforms the 12 V dc of the battery (when switched off in the primary) into a spike of as much as 30 kV in the secondary.

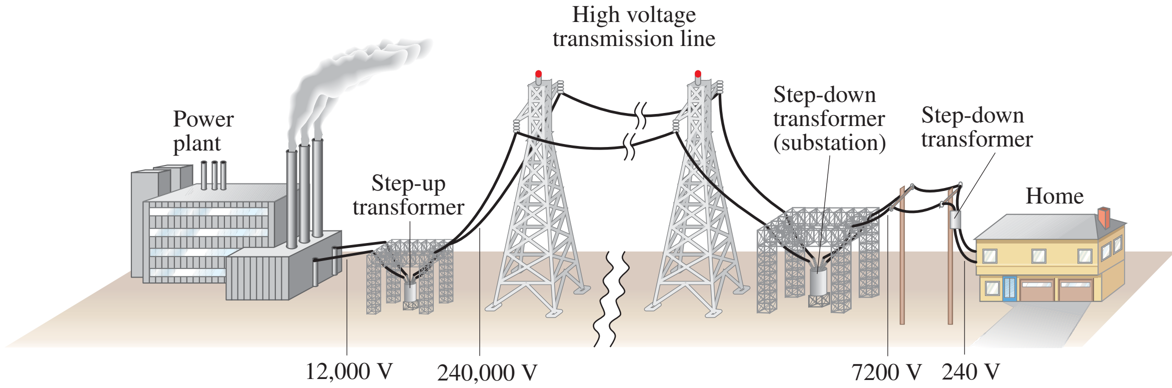


FIGURE 21–25 The transmission of electric power from power plants to homes makes use of transformers at various stages.

PHYSICS APPLIED
Transformers help power transmission

Transformers play an important role in the transmission of electricity. Power plants are often situated some distance from metropolitan areas, so electricity must then be transmitted over long distances (Fig. 21–25). There is always some power loss in the transmission lines, and this loss can be minimized if the power is transmitted at high voltage, using transformers, as the following Example shows.

EXAMPLE 21–11 **Transmission lines.** An average of 120 kW of electric power is sent to a small town from a power plant 10 km away. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if the power is transmitted at (*a*) 240 V and (*b*) 24,000 V.

APPROACH We cannot use $P = V^2/R$ because if R is the resistance of the transmission lines, we don't know the voltage drop along them. The given voltages are applied across the lines plus the load (the town). But we can determine the current I in the lines $(= P/V)$, and then find the power loss from $P_L = I^2R$, for both cases (*a*) and (*b*).

SOLUTION (*a*) If 120 kW is sent at 240 V, the total current will be

$$I = \frac{P}{V} = \frac{1.2 \times 10^5\ \text{W}}{2.4 \times 10^2\ \text{V}} = 500\ \text{A}.$$

The power loss in the lines, P_L, is then

$$P_L = I^2R = (500\ \text{A})^2(0.40\ \Omega) = 100\ \text{kW}.$$

Thus, over 80% of all the power would be wasted as heat in the power lines!
(*b*) If 120 kW is sent at 24,000 V, the total current will be

$$I = \frac{P}{V} = \frac{1.2 \times 10^5\ \text{W}}{2.4 \times 10^4\ \text{V}} = 5.0\ \text{A}.$$

The power loss in the lines is then

$$P_L = I^2R = (5.0\ \text{A})^2(0.40\ \Omega) = 10\ \text{W},$$

which is less than $\frac{1}{100}$ of 1%: a far better efficiency.

NOTE We see that the higher voltage results in less current, and thus less power is wasted as heat in the transmission lines. It is for this reason that power is usually transmitted at very high voltages, as high as 700 kV.

The great advantage of ac, and a major reason it is in nearly universal use†, is that the voltage can easily be stepped up or down by a transformer. The output voltage of an electric generating plant is stepped up prior to transmission. Upon arrival in a city, it is stepped down in stages at electric substations prior to distribution. The voltage in lines along city streets is typically 2400 V or 7200 V and is stepped down to 240 V or 120 V for home use by transformers (Figs. 21–22 and 21–25).

†DC transmission along wires does exist, and has some advantages (if the current is constant, there is no induced current in nearby conductors as there is with ac). But boosting to high voltage and down again at the receiving end requires more complicated electronics.

PHYSICS APPLIED
Charging phones, cars, etc., by induction

Wireless Transmission of Power—Inductive Charging

Many devices with rechargeable batteries, like cell phones, cordless phones, and even electric cars, can be recharged using a direct metal contact between the device and the charger. But devices can also be charged "wirelessly" by induction, without the need for exposed electric contacts. The electric toothbrush shown in Fig. 21–26 sits on a plastic base. Inside the base is a "primary coil" connected to an ac outlet. Inside the toothbrush is a "secondary coil" in which a current is induced due to the changing magnetic field produced by the changing current in the primary coil. The current induced in the secondary coil charges the rechargeable batteries. (Not an option for ordinary AA or AAA batteries which are *not* rechargeable.) The effect is like a transformer—except here there is no iron to contain the field lines, so there is less efficiency. But you can separate the two parts (toothbrush and charger) and brush your teeth. Many heart pacemakers are given power inductively: power in an external coil is transmitted to a secondary coil in the pacemaker (Fig. 19–25) inside the person's body near the heart. Inductive charging is also a possible means for recharging an electric car's batteries.

Wireless transmission of power must be done over short distances to maintain a reasonable efficiency. Wireless transmission of signals (information) can be done over great distances (Section 22–7) because even fairly low power signals can be detected, and it is the information in the signal voltages that counts, not power.

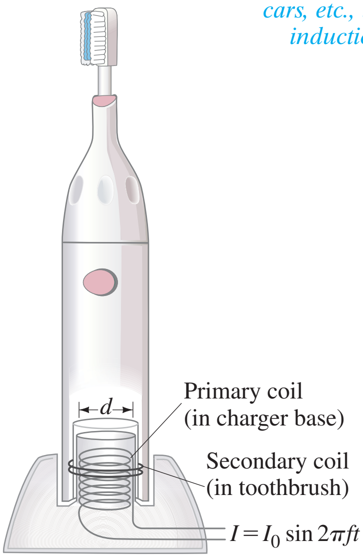


FIGURE 21–26 This electric toothbrush contains rechargeable batteries which are being recharged as it sits on its base. Charging occurs from a primary coil in the base to a secondary coil in the toothbrush. The toothbrush can be lifted from its base when you want to brush your teeth.

*21–8 Information Storage: Magnetic and Semiconductor; Tape, Hard Drive, RAM

PHYSICS APPLIED
Hard drive

*Magnetic Storage: Read/Write on Tape and Disks

Recording and playback on tape or disk is done by magnetic **heads**. Magnetic tapes contain a thin layer of ferromagnetic oxide on a thin plastic tape. Computer **hard drives** (HD) store digital information (applications and data): they have a thin layer of ferromagnetic material on the surface of each rotating disk or platter, Fig. 21–27a. During recording of an audio or video signal on tape, or "writing" on a hard drive, the voltage is sent to the recording head which acts as a tiny electromagnet (Fig. 21–27b) that magnetizes the tiny section of tape or disk passing the narrow gap in the head at each instant. During playback, or "reading" of an HD, the changing magnetism of the moving tape or disk at the gap causes corresponding changes in the magnetic field within the soft-iron head, which in turn induces an emf in the coil (Faraday's law). This induced emf is the output signal that can be processed by the computer, or for audio can be amplified and sent to a loudspeaker (for video to a monitor or TV).

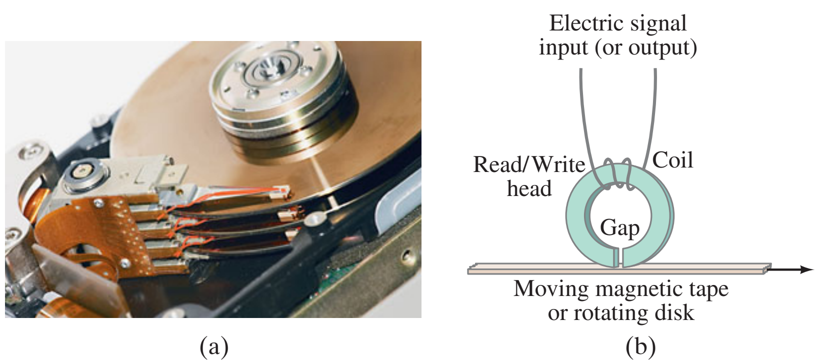


FIGURE 21–27 (a) Photo of a hard drive showing several platters and read/write heads that can quickly move from the edge of the disk to the center. (b) Read/Write (playback/recording) head for disk or tape. In writing or recording, the electric input signal to the head, which acts as an electromagnet, magnetizes the passing tape or disk. In reading or playback, the changing magnetic field of the passing tape or disk induces a changing magnetic field in the head, which in turn induces in the coil an emf that is the output signal.

Audio and video signals may be **analog**, varying continuously in amplitude over time: the variation in degree of magnetization at sequential points reflects the variation in amplitude and frequency of the audio or video signal. In modern equipment, analog signals (say from a microphone) are electronically converted to **digital**—which means a series of **bits**, each of which is a "1" or a "0", that forms a **binary code** as discussed in Section 17–10. (Recall also, 8 bits in a row = 1 **byte**.) Computers process only digital information.

CD-ROMs, CDs (audio compact discs), and DVDs (digital video discs) are read by an **optical drive** (not magnetic): a laser emits a narrow beam of light that reflects off the "grooves" of the rotating disc containing "pits" as described in Section 28–11.

PHYSICS APPLIED
CDs and DVDs

*Semiconductor Memory: DRAM, Flash

Basic to your computer is its **random access memory** (**RAM**). This is where the information you are working with at any given time is temporarily stored and manipulated by you. Each data storage location can be accessed and read (or written) directly and quickly, so you don't have to wait. In contrast, hard drives, tape, flash and external devices are more permanent **storage**, and they are much slower to access because the data must be searched for, sequentially, such as along the circular tracks of hard drives (Fig. 21–27a). Programs, applications, and data that you want to use are imported by the computer into the RAM from their more permanent (and more slowly accessed) storage area.†

RAM is based on semiconductor technology, storing the binary bits ("0" or "1") as electric charge or voltage. Some computers may use semiconductors also for long-term storage ("flash memory") in place of a hard drive.

A common type of RAM is **dynamic random access memory** or **DRAM**, which uses arrays of transistors known as MOSFETs (metal-oxide semiconductor field-effect transistors). Transistors will be discussed in Section 29–10, but we already encountered them in Section 17–11 about TV screen addressing, Fig. 17–34, which we show again here, Fig. 21–28. A MOSFET transistor in RAM serves basically as an on–off switch: the voltage on the **gate** terminal acts to control the conductivity between the **source** and the **drain** terminals, thus allowing current to flow (or not) between them.

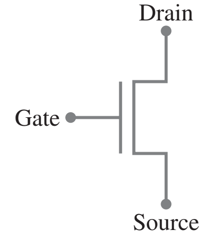
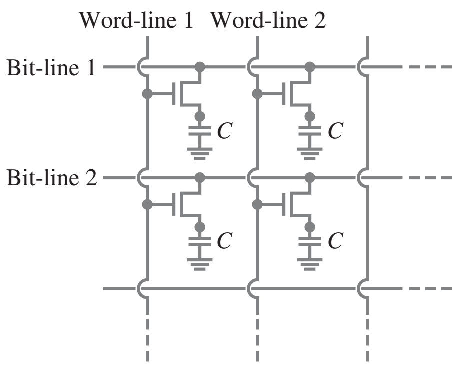


FIGURE 21–28 Symbol for a MOSFET transistor. The gate acts to attract or repel charge, and thus open or close the connection along the semiconductor that connects source and drain.

Each memory "cell," which in DRAM consists of one transistor and a capacitor, stores one bit (= a "0" or a "1"). Each cell is extremely small physically, less than 100 nm across.‡ Typical DRAM chips (integrated circuits) contain billions of these memory cells. To see how they work, we look at a tiny part, the simple four-cell array shown in Fig. 21–29. One side of each cell capacitor is grounded; the other side is connected to the transistor source. The drain of each transistor is connected to a very thin conducting wire or "line," a **bit-line**, that runs across the array of cells. Each gate is connected to a **word-line**. A particular bit is a "1" or a "0" depending on whether the capacitor of the cell is charged to a voltage V (maybe 5 V) or is at zero (uncharged, or at a very small voltage).

FIGURE 21–29 A tiny 2 × 2 cell, part of a simple DRAM array. The word-lines and bit-lines do not touch each other where they cross.



To **write** data, say on the upper left cell in Fig. 21–29, word-line-1 is given a high enough pulse of voltage to "turn on" the transistor. That is, the high gate voltage attracts charge and allows bit-line-1 and the capacitor to be connected. Thus charge can flow from bit-line-1 to the capacitor, charging it either to V or to 0, depending on the bit-line-1 voltage at that moment, thus writing a "1" or a "0".

The lower left cell in Fig. 21–29 can be written at the same time by setting bit-line-2 voltage to V or zero.

Now let us see a simple way to **read** a cell. In order to read the data stored ("1" or "0") on the upper left cell, a voltage of about $\frac{1}{2}V$ is given to bit-line-1. Then word-line-1 is given enough voltage to turn on the transistor and connect bit-line-1 to the capacitor. The capacitor, if uncharged (= "0"), will now drag charge from bit-line-1 and the bit-line voltage will drop *below* $\frac{1}{2}V$. If the capacitor is already charged to V (= "1"), the connection to bit-line-1 will raise bit-line-1's voltage to *above* $\frac{1}{2}V$. A sensor at the end of bit-line-1 will detect either change in voltage (increase means it reads a "1", decrease a "0"). All cells connected to one word-line are read at the same moment. The capacitor voltage has been altered by the small charge flow during the reading process. So that cell or bit which has just been read needs to be written again, or "refreshed."

†Computer specifications may use "memory" for the random access (fast) memory, and "storage" for the long-term (and slower access) information on hard drives, flash drives, and related devices.

‡At 100 nm, 10^5 bits can fit along a 1-cm line, $(1\text{ cm}/100\text{ nm}) = 10^{-2}\text{ m}/10^{-7}\text{ m}$. So a square, 1 cm on a side, can hold $10^5 \times 10^5 = 10^{10} = 10$ Gbits ≈ 1 GB (gigabyte). Today, cells are even smaller than 100 nm: a $(30\text{ nm})^2$ cell can hold ≈ 10 GB in a 1 cm² area.

The transistors are imperfect switches and allow the charge on the tiny capacitors in each cell to be "leaky" and lose charge fairly quickly, so every cell has to be read and rewritten (refreshed) many times per second. The D in DRAM stands for this "dynamic" refreshing action. If the power is turned off, the capacitors lose their charge and the data are lost. DRAM is thus referred to as being **volatile** memory, whereas a hard drive keeps its (magnetic) memory even when the electric power is off and is called **nonvolatile** memory (doesn't "evaporate").

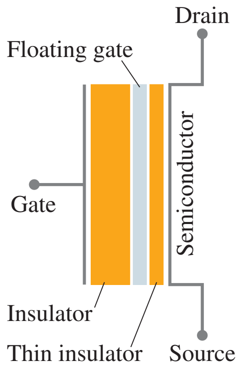


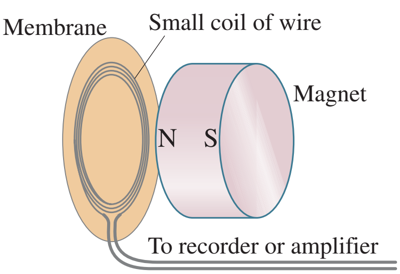
FIGURE 21–30 A floating gate nonvolatile memory cell (NVM).

Flash memory is also made of semiconductor material on tiny "chips." The transistor structures are more complicated, and are able to keep the data even without power so they are nonvolatile. Each MOSFET contains a second gate (the **floating gate**) insulated on both faces, and can hold charge for many years. Charged or not corresponds to a "1" or a "0" bit. Figure 21–30 is a diagram of such an **NVM** (nonvolatile memory) cell. The floating gate is insulated from the standard gate and the semiconductor connecting source and drain. A high positive voltage on the gate (+20 V) forces electrons in the semiconductor (at 0 V) to pass through the thin insulator into the floating gate by a process of quantum mechanical **tunneling** (discussed in Section 30–12). This charge is stored on the floating gate as a "1" bit. The erase process is done by applying the opposite (−20 V) voltage to force electrons to tunnel out of the floating gate, returning it to the uncharged state (= a "0" bit). The erase process is slow (milliseconds vs. ns for DRAM), so erasure is done in large blocks of memory. Flash memory† is slower to read or write, and is too slow to use as RAM. Instead, flash memory can be used in place of a hard drive as general storage in computers and tablets, and may be called a "solid state device" (**SSD**). Flash is also used for flash drives, memory cards (such as SD cards), thumb drives, cell phone and portable player memory, and external computer memory.

Magnetoresistive RAM (**MRAM**) is a recent development, involving (again) magnetic properties. One cell (storing one bit) consists of two tiny ferromagnetic plates (separated by an insulator), one of which is permanently magnetized. The other plate can be magnetized in one direction or the other, for a "1" or a "0", by current in nearby wires. Cell size is a bit large, but MRAM is fast and nonvolatile (no power and no refresh needed) and therefore has the potential to be used as any type of memory.

*21–9 Applications of Induction: Microphone, Seismograph, GFCI

FIGURE 21–31 Diagram of a microphone that works by induction.



*Microphone

The condenser microphone was discussed in Section 17–7. Many other types operate on the principle of induction. In one form, a microphone is just the inverse of a loudspeaker (Section 20–10). A small coil connected to a membrane is suspended close to a small permanent magnet, as shown in Fig. 21–31. The coil moves in the magnetic field when sound waves strike the membrane, and this motion induces an emf in the moving coil. The frequency of the induced emf will be just that of the impinging sound waves, and this emf is the "signal" that can be amplified and sent to loudspeakers or recorder.

*Credit Card Reader

PHYSICS APPLIED
Credit card

When you pass a credit card through a reader at a store, the magnetic stripe on the back of the card passes over a read head just as for a computer hard drive. The magnetic stripe contains personal information about your account and connects by telephone line for approval from your credit card company. Newer cards use semiconductor chips that are more difficult to fraudulently copy.

†Why the name "Flash"? It may come from the erase process: large blocks erased "in a flash," and/or because the earliest floating gate memories were erased by a flash of UV light which ejected the stored electrons.

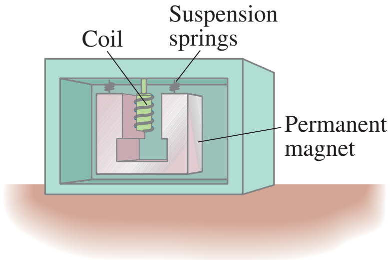


FIGURE 21–32 One type of seismograph, in which the coil is fixed to the case and moves with the Earth's surface. The magnet, suspended by springs, has inertia and does not move instantaneously with the coil (and case), so there is relative motion between magnet and coil.

* Seismograph

PHYSICS APPLIED
Seismograph

In geophysics, a **seismograph** measures the intensity of earthquake waves using a magnet and a coil of wire. Either the magnet or the coil is fixed to the case, and the other is inertial (suspended by a spring; Fig. 21–32). The relative motion of magnet and coil when the surface of the Earth shakes induces an emf output.

* Ground Fault Circuit Interrupter (GFCI)

Fuses and circuit breakers (Sections 18–6 and 20–7) protect buildings from electricity-induced fire, and apparatus from damage, due to undesired high currents. But they do not turn off the current until it is very much greater than that which can cause permanent damage to humans or death ($\approx 100\,\text{mA}$). If fast enough, they may protect humans in some cases, such as very high currents due to short circuits. A **ground fault circuit interrupter** (GFCI) is meant above all to protect humans.

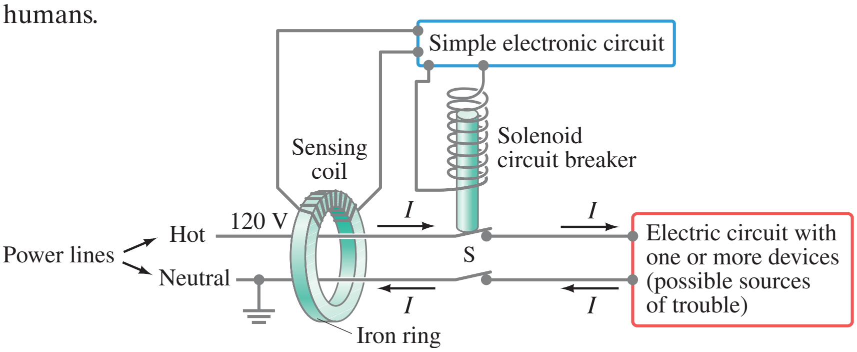


FIGURE 21–33 A ground fault circuit interrupter (GFCI).

PHYSICS APPLIED
GFCI

Electromagnetic induction is the physical basis of a GFCI. As shown in Fig. 21–33, the two conductors of a power line connected to an electric circuit or device (red) pass through a small iron ring. Around the ring are many loops of thin wire that serve as a sensing coil. Under normal conditions (no ground fault), the current moving in the hot power wire is exactly balanced by the returning current in the neutral wire. If something goes wrong and the hot wire touches the ungrounded metal case of the device or appliance, some of the entering current can pass through a person who touches the case and then to ground (a **ground fault**). Then the return current in the neutral wire will be less than the entering current in the hot wire, so there is a *net current* passing through the GFCI's iron ring. Because the current is ac, it is changing and that current difference produces a changing magnetic field in the iron, thus inducing an emf in the sensing coil wrapped around the iron. For example, if a device draws 8.0 A, and there is a ground fault through a person of 100 mA (= 0.1 A), then 7.9 A will appear in the neutral wire. The emf induced in the sensing coil by this 100-mA difference is amplified by a simple transistor circuit and sent to its own solenoid circuit breaker that opens the circuit at the switch S, thus protecting your life.

If the case of the faulty device is grounded, the difference in current is even higher when there is a fault, and the GFCI trips very quickly.

GFCIs can sense current differences as low as 5 mA and react in 1 ms, saving lives. They can be small to fit as a wall outlet (Fig. 21–34a), or as a plug-in unit into which you plug a hair dryer or toaster (Fig. 21–34b). It is especially important to have GFCIs installed in kitchens, in bathrooms, outdoors, and near swimming pools, where people are most in danger of touching ground. GFCIs always have a "test" button (to be sure the GFCI itself works) and a "reset" button (after it goes off).

FIGURE 21–34 (a) A GFCI wall outlet. GFCIs can be recognized by their "test" and "reset" buttons. (b) Add-on GFCI that plugs into outlet.

(a)

(b)

*21–10 Inductance

*Mutual Inductance

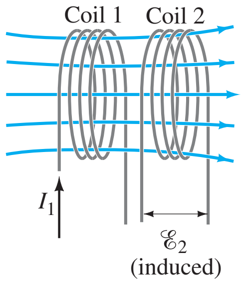


FIGURE 21–35 A changing current in one coil will induce a current in the second coil.

If two coils of wire are near one another, as in Fig. 21–35, a changing current in one will induce an emf in the other. We apply Faraday's law to coil 2: the emf $\mathscr{E}_2$ induced in coil 2 is proportional to the rate of change of magnetic flux passing through it. A changing flux in coil 2 is produced by a changing current I_1 in coil 1. So $\mathscr{E}_2$ is proportional to the rate of change of the current in coil 1:

$$\mathscr{E}_2 = -M \frac{\Delta I_1}{\Delta t}, \tag{21–8a}$$

where we assume the time interval Δt is very small, and the constant of proportionality, M, is called the **mutual inductance**. (The minus sign is because of Lenz's law, the induced emf opposes the changing flux.) Mutual inductance has units of $\mathrm{V \cdot s/A} = \Omega \cdot \mathrm{s}$, which is called the **henry** (H), after Joseph Henry: $1\,\mathrm{H} = 1\,\Omega \cdot \mathrm{s}$.

The mutual inductance M is a "constant" in that it does not depend on I_1; M depends on "geometric" factors such as the size, shape, number of turns, and relative positions of the two coils, and also on whether iron (or other ferromagnetic material) is present. For example, the farther apart the two coils are in Fig. 21–35, the fewer lines of flux can pass through coil 2, so M will be less. If we consider the inverse situation—a changing current in coil 2 inducing an emf in coil 1—the proportionality constant, M, turns out to have the same value,

$$\mathscr{E}_1 = -M \frac{\Delta I_2}{\Delta t}. \tag{21–8b}$$

PHYSICS APPLIED
Pacemaker

A transformer is an example of mutual inductance in which the coupling is maximized so that nearly all flux lines pass through both coils. Mutual inductance has other uses as well, including inductive charging of cell phones, electric cars, and other devices with rechargeable batteries, as we discussed in Section 21–7. Some types of pacemakers used to maintain blood flow in heart patients (Section 19–6) receive their power from an external coil which is transmitted via mutual inductance to a second coil in the pacemaker near the heart. This type has the advantage over battery-powered pacemakers in that surgery is not needed to replace a battery when it wears out.

*Self-Inductance

The concept of inductance applies also to an isolated single coil. When a changing current passes through a coil or solenoid, a changing magnetic flux is produced inside the coil, and this in turn induces an emf. This induced emf opposes the change in flux (Lenz's law); it is much like the back emf generated in a motor. (For example, if the current through the coil is increasing, the increasing magnetic flux induces an emf that opposes the original current and tends to retard its increase.) The induced emf $\mathscr{E}$ is proportional to the rate of change in current (and is in the direction opposed to the change, hence the minus sign):

$$\mathscr{E} = -L \frac{\Delta I}{\Delta t}. \tag{21–9}$$

The constant of proportionality L is called the **self-inductance**, or simply the **inductance** of the coil. It, too, is measured in henrys. The magnitude of L depends on the size and shape of the coil and on the presence of an iron core.

An ac circuit (Section 18–7) always contains some inductance, but often it is quite small unless the circuit contains a coil of many loops or turns. A coil that has significant self-inductance L is called an **inductor**. It is shown on circuit diagrams by the symbol

. [inductor symbol]

CONCEPTUAL EXAMPLE 21–12 **Direction of emf in inductor.** Current passes through the coil in Fig. 21–36 from left to right as shown. (*a*) If the current is increasing with time, in which direction is the induced emf? (*b*) If the current is decreasing in time, what then is the direction of the induced emf?

RESPONSE (*a*) From Lenz's law we know that the induced emf must oppose the change in magnetic flux. If the current is increasing, so is the magnetic flux. The induced emf acts to oppose the increasing flux, which means it acts like a source of emf that opposes the outside source of emf driving the current. So the induced emf in the coil acts to oppose I in Fig. 21–36a. In other words, the inductor might be thought of as a battery with a positive terminal at point A (tending to block the current entering at A), and negative at point B.

(*b*) If the current is decreasing, then by Lenz's law the induced emf acts to bolster the flux—like a source of emf reinforcing the external emf. The induced emf acts to increase I in Fig. 21–36b, so in this situation you can think of the induced emf as a battery with its negative terminal at point A to attract more current (conventional, +) to move to the right.

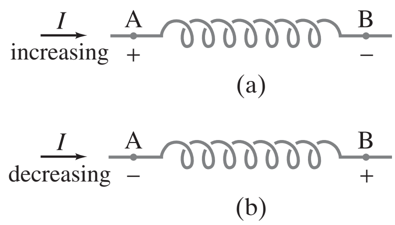


FIGURE 21–36 Example 21–12.

EXAMPLE 21–13 **Solenoid inductance.** (*a*) Determine a formula for the self-inductance L of a long tightly wrapped solenoid coil of length ℓ and cross-sectional area A, that contains N turns (or loops) of wire. (*b*) Calculate the value of L if $N = 100$, $\ell = 5.0\,\text{cm}$, $A = 0.30\,\text{cm}^2$, and the solenoid is air filled.

APPROACH The induced emf in a coil can be determined either from Faraday's law $\left(\mathscr{E} = -N\,\Delta\Phi_B/\Delta t\right)$ or the self-inductance $\left(\mathscr{E} = -L\,\Delta I/\Delta t\right)$. If we equate these two expressions, we can solve for the inductance L since we know how to calculate the flux Φ_B for a solenoid using Eq. 20–8 ($B = \mu_0 IN/\ell$).

SOLUTION (*a*) We equate Faraday's law (Eq. 21–2b) and Eq. 21–9 for the inductance:

$$\mathscr{E} = -N\frac{\Delta\Phi_B}{\Delta t} = -L\frac{\Delta I}{\Delta t},$$

and solve for L:

$$L = N\frac{\Delta\Phi_B}{\Delta I}.$$

We know $\Phi_B = BA$ (Eq. 21–1), and Eq. 20–8 gives us the magnetic field B for a solenoid, $B = \mu_0 NI/\ell$, so the magnetic flux inside the solenoid is

$$\Phi_B = \frac{\mu_0 NIA}{\ell}.$$

Any change in current, ΔI, causes a change in flux

$$\Delta\Phi_B = \frac{\mu_0 N\,\Delta I\,A}{\ell}.$$

We put this into our equation above for L:

$$L = N\frac{\Delta\Phi_B}{\Delta I} = \frac{\mu_0 N^2 A}{\ell}.$$

(*b*) Using $\mu_0 = 4\pi \times 10^{-7}\,\text{T}\cdot\text{m/A}$, and putting in values given,

$$L = \frac{(4\pi \times 10^{-7}\,\text{T}\cdot\text{m/A})(100)^2(3.0 \times 10^{-5}\,\text{m}^2)}{(5.0 \times 10^{-2}\,\text{m})} = 7.5\,\mu\text{H}.$$

*21–11 Energy Stored in a Magnetic Field

In Section 17–9 we saw that the energy stored in a capacitor is equal to $\frac{1}{2}CV^2$. By using a similar argument, it can be shown that the energy U stored in an inductance L, carrying a current I, is

$$U = \text{energy} = \tfrac{1}{2}LI^2.$$

Just as the energy stored in a capacitor can be considered to reside in the electric field between its plates, so the energy in an inductor can be considered to be stored in its magnetic field.

To write the energy in terms of the magnetic field, we quote the result of Example 21–13 that the inductance of a solenoid is $L = \mu_0 N^2 A/\ell$. The magnetic field B in a solenoid is related to the current I (see Eq. 20–8) by $B = \mu_0 NI/\ell$. Thus, $I = B\ell/\mu_0 N$, and

$$U = \text{energy} = \tfrac{1}{2}LI^2 = \frac{1}{2}\left(\frac{\mu_0 N^2 A}{\ell}\right)\left(\frac{B\ell}{\mu_0 N}\right)^2 = \frac{1}{2}\frac{B^2}{\mu_0}A\ell.$$

We can think of this energy as residing in the volume enclosed by the windings, which is $A\ell$. Then the energy per unit volume, or **energy density**, is

$$u = \text{energy density} = \frac{1}{2}\frac{B^2}{\mu_0}. \qquad \textbf{(21–10)}$$

This formula, which was derived for the special case of a solenoid, can be shown to be valid for any region of space where a magnetic field exists. If a ferromagnetic material is present, μ_0 is replaced by μ. This equation is analogous to that for an electric field, $\frac{1}{2}\epsilon_0 E^2$, Section 17–9.

*21–12 *LR* Circuit

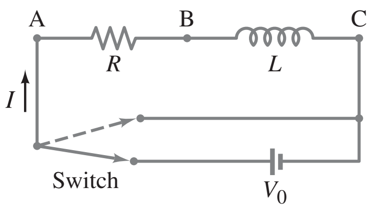
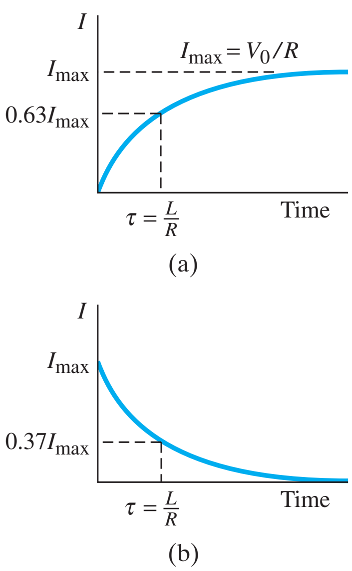


FIGURE 21–37 *LR* circuit.

FIGURE 21–38 (a) Growth of current in an *LR* circuit when connected to a battery. (b) Decay of current when the *LR* circuit is shorted out (battery is out of the circuit).



Any inductor will have some resistance. We represent an inductor by drawing the inductance L and its resistance R separately, as in Fig. 21–37. The resistance R could also include any other resistance in the circuit. Now we ask, what happens when a battery of voltage V_0 is connected in series to such an LR circuit? At the instant the switch connecting the battery is closed, the current starts to flow. It is opposed by the induced emf in the inductor because of the changing current. However, as soon as current starts to flow, there is a voltage drop across the resistance ($V = IR$). Hence, the voltage drop across the inductance is reduced and the current increases less rapidly. The current thus rises gradually, as shown in Fig. 21–38a, and approaches the steady value $I_{max} = V_0/R$ when there is no more emf in the inductor (I is no longer changing) so all the voltage drop is across the resistance. The shape of the curve for I as a function of time is

$$I = \left(\frac{V_0}{R}\right)\left(1 - e^{-t/\tau}\right), \qquad [LR \text{ circuit with emf}]$$

where e is the number $e = 2.718\cdots$ (see Section 19–6) and

$$\tau = \frac{L}{R}$$

is the **time constant** of the circuit. When $t = \tau$, then $\left(1 - e^{-1}\right) = 0.63$, so τ is the time required for the current to reach $0.63I_{max}$.

Next, if the battery is suddenly switched out of the circuit (dashed line in Fig. 21–37), it takes time for the current to drop to zero, as shown in Fig. 21–38b. This is an exponential decay curve given by

$$I = I_{max}e^{-t/\tau}. \qquad [LR \text{ circuit without emf}]$$

The time constant τ is the time for the current to decrease to $0.37I_{max}$ (37% of the original value), and again equals L/R.

These graphs show that there is always some "lag time" or "reaction time" when an electromagnet, for example, is turned on or off. We also see that an LR circuit has properties similar to an RC circuit (Section 19–6). Unlike the capacitor case, however, the time constant here is *inversely* proportional to R.

*21–13 AC Circuits and Reactance

We have previously discussed circuits that contain combinations of resistor, capacitor, and inductor, but only when they are connected to a dc source of emf or to zero voltage. Now we discuss these circuit elements when they are connected to a source of alternating voltage that produces an alternating current (ac).

First we examine, one at a time, how a resistor, a capacitor, and an inductor behave when connected to a source of alternating voltage, represented by the symbol

—(~)— [alternating voltage]

which produces a sinusoidal voltage of frequency f. We assume in each case that the emf gives rise to a current

$$I = I_0 \cos 2\pi f t,$$

where t is time and I_0 is the peak current. Remember (Section 18–7) that $V_{\mathrm{rms}} = V_0/\sqrt{2}$ and $I_{\mathrm{rms}} = I_0/\sqrt{2}$ (Eq. 18–8).

* Resistor

When an ac source is connected to a resistor as in Fig. 21–39a, the current increases and decreases with the alternating voltage according to Ohm's law,

$$V = IR = I_0 R \cos 2\pi f t = V_0 \cos 2\pi f t$$

where $V_0 = I_0 R$ is the peak voltage. Figure 21–39b shows the voltage (red curve) and the current (blue curve) as a function of time. Because the current is zero when the voltage is zero and the current reaches a peak when the voltage does, we say that the current and voltage are **in phase**. Energy is transformed into heat (Section 18–7), at an average rate $\overline{P} = \overline{IV} = I^2_{\mathrm{rms}} R = V^2_{\mathrm{rms}}/R$.

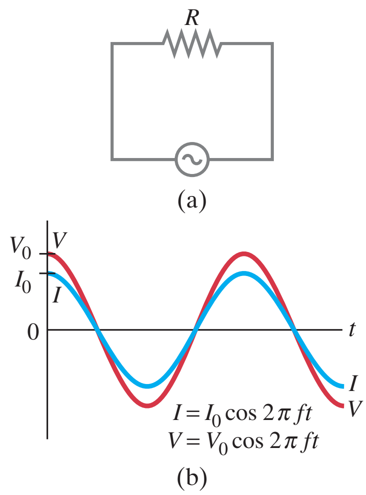


FIGURE 21–39 (a) Resistor connected to an ac source. (b) Current (blue curve) is in phase with the voltage (red) across a resistor.

* Inductor

In Fig. 21–40a an inductor of inductance L (symbol —ᴗᴗᴗᴗ—) is connected to the ac source. We ignore any resistance it might have (it is usually small). The voltage applied to the inductor will be equal to the "back" emf generated in the inductor by the changing current as given by Eq. 21–9. This is because the sum of the electric potential changes around any closed circuit must add up to zero, by Kirchhoff's rule. Thus

$$V - L\frac{\Delta I}{\Delta t} = 0$$

or

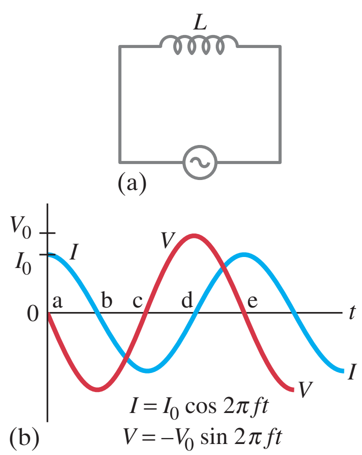
$$\frac{\Delta I}{\Delta t} = \frac{V}{L}$$

where V is the sinusoidally varying voltage of the source and $L\,\Delta I/\Delta t$ is the voltage induced in the inductor. According to the last equation, I is increasing most rapidly when V has its maximum value, $V = V_0$. And I will be decreasing most rapidly when $V = -V_0$. These two instants correspond to points d and b on the graph of voltage versus time in Fig. 21–40b. By going point by point in this manner, the curve of V versus t as compared to that for I versus t can be constructed, and they are shown by the blue and red lines, respectively, in Fig. 21–40b. Notice that the current reaches its peaks (and troughs) $\frac{1}{4}$ cycle after the voltage does. We say that the

current lags the voltage by 90° for an inductor.

Because the current and voltage in an inductor are *out of phase* by 90°, the product IV (= power) is as often positive as it is negative (Fig. 21–40b). So no energy is transformed in an inductor on average; and no energy is dissipated as thermal energy.

FIGURE 21–40 (a) Inductor connected to an ac source. (b) Current (blue curve) lags voltage (red curve) by a quarter cycle, or 90°.



Just as a resistor impedes the flow of charge, so too an inductor impedes the flow of charge in an alternating current due to the back emf produced. For a resistor R, the current and voltage are related by $V = IR$. We can write a similar relation for an inductor:

$$V = IX_L, \quad \begin{bmatrix}\text{rms or peak values,} \\ \text{not at any instant}\end{bmatrix} \tag{21–11a}$$

where X_L is called the **inductive reactance**. X_L has units of ohms. The quantities V and I in Eq. 21–11a can refer either to rms for both, or to peak values for both (see Section 18–7). Although this equation can relate the peak values, the peak current and voltage are not reached at the same time; so Eq. 21–11a is *not valid at a particular instant*, as is the case for a resistor ($V = IR$). Careful calculation (using calculus), as well as experiment, shows that

$$X_L = \omega L = 2\pi f L, \tag{21–11b}$$

where $\omega = 2\pi f$ and f is the frequency of the ac.

For example, the inductive reactance of a 0.300-H inductor at 120 V and 60.0 Hz is $X_L = 2\pi f L = (6.28)(60.0\,\text{s}^{-1})(0.300\,\text{H}) = 113\,\Omega$.

* Capacitor

When a capacitor is connected to a battery, the capacitor plates quickly acquire equal and opposite charges; but no steady current flows in the circuit. A capacitor prevents the flow of a dc current. But if a capacitor is connected to an alternating source of voltage, as in Fig. 21–41a, an alternating current will flow continuously. This can happen because when the ac voltage is first turned on, charge begins to flow and one plate acquires a negative charge and the other a positive charge. But when the voltage reverses itself, the charges flow in the opposite direction. Thus, for an alternating applied voltage, an ac current is present in the circuit continuously.

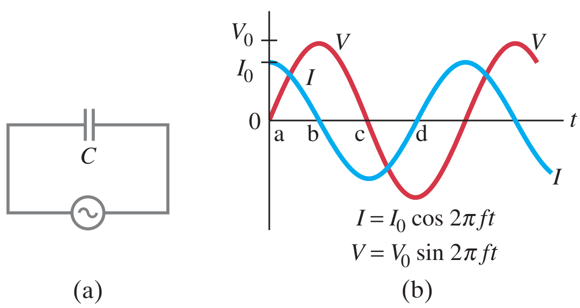


FIGURE 21–41 (a) Capacitor connected to an ac source. (b) Current leads voltage by a quarter cycle, or 90°.

The applied voltage must equal the voltage across the capacitor: $V = Q/C$, where C is the capacitance and Q the charge on the plates. Thus the charge Q on the plates is in phase with the voltage. But what about the current I? At point a in Fig. 21–41b, when the voltage is zero and starts increasing, the charge on the plates is zero. Thus charge flows readily toward the plates and the current I is large. As the voltage approaches its maximum of V_0 (point b in Fig. 21–41b), the charge that has accumulated on the plates tends to prevent more charge from flowing, so the current I drops to zero at point b. Thus the current follows the blue curve in Fig. 21–41b. Like an inductor, the voltage and current are out of phase by 90°. But for a capacitor, the current reaches its peaks $\frac{1}{4}$ cycle before the voltage does, so we say that the

current leads the voltage by 90° for a capacitor.

CAUTION
Only resistance dissipates energy

Because the current and voltage are out of phase, the average power dissipated is zero, just as for an inductor. Thus *only a resistance will dissipate energy* as thermal energy in an ac circuit.

A relationship between the applied voltage and the current in a capacitor can be written just as for an inductance:

$$V = IX_C, \qquad \begin{bmatrix}\text{rms or peak}\\ \text{values}\end{bmatrix} \qquad \textbf{(21–12a)}$$

where X_C is called the **capacitive reactance** and has units of ohms. V and I can both be rms or both maximum (V_0 and I_0); X_C depends on both the capacitance C and the frequency f:

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}, \qquad \textbf{(21–12b)}$$

where $\omega = 2\pi f$. For dc conditions, $f = 0$ and X_C becomes infinite, as it should because a capacitor does not pass dc current.

EXAMPLE 21–14 **Capacitor reactance.** What is the rms current in the circuit of Fig. 21–41a if $C = 1.00\,\mu\text{F}$ and $V_{\text{rms}} = 120\text{ V}$? Calculate for (*a*) $f = 60.0\text{ Hz}$, and then for (*b*) $f = 6.00 \times 10^5\text{ Hz}$.

APPROACH We find the reactance using Eq. 21–12b, and solve for current in the equivalent form of Ohm's law, Eq. 21–12a.

SOLUTION (*a*) $X_C = 1/2\pi f C = 1/(2\pi)(60.0\text{ s}^{-1})(1.00 \times 10^{-6}\text{ F}) = 2.65\text{ k}\Omega$. The rms current is (Eq. 21–12a):

$$I_{\text{rms}} = \frac{V_{\text{rms}}}{X_C} = \frac{120\text{ V}}{2.65 \times 10^3\,\Omega} = 45.2\text{ mA}.$$

(*b*) For $f = 6.00 \times 10^5\text{ Hz}$, X_C will be $0.265\,\Omega$ and $I_{\text{rms}} = 452\text{ A}$, vastly larger!

NOTE The dependence on f is dramatic. For high frequencies, the capacitive reactance is very small.

Two common applications of capacitors are illustrated in Figs. 21–42a and b. In Fig. 21–42a, circuit A is said to be capacitively coupled to circuit B. The purpose of the capacitor is to prevent a dc voltage from passing from A to B but allowing an ac signal to pass relatively unimpeded (if C is sufficiently large). In Fig. 21–42b, the

PHYSICS APPLIED
Capacitors as filters

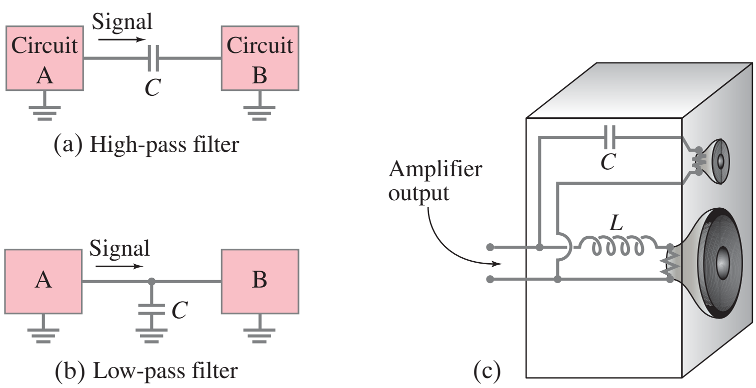


FIGURE 21–42 (a) and (b): Two common uses for a capacitor as a filter. (c) Simple loudspeaker cross-over.

capacitor also passes ac and not dc. In this case, a dc voltage can be maintained between circuits A and B, but an ac signal leaving A passes to ground instead of into B. Thus the capacitor in Fig. 21–42b acts like a **filter** when a constant dc voltage is required; any sharp variation in voltage passes to ground instead of into circuit B.

EXERCISE F The capacitor C in Fig. 21–42a is often called a "high-pass" filter, and the one in Fig. 21–42b a "low-pass" filter. Explain why.

Loudspeakers having separate "woofer" (low-frequency speaker) and "tweeter" (high-frequency speaker) may use a simple "cross-over" that consists of a capacitor in the tweeter circuit to impede low-frequency signals, and an inductor in the woofer circuit to impede high-frequency signals $(X_L = 2\pi f L)$. Hence mainly low-frequency sounds reach and are emitted by the woofer. See Fig. 21–42c.

PHYSICS APPLIED
Loudspeaker cross-over

*21–14 *LRC* Series AC Circuit

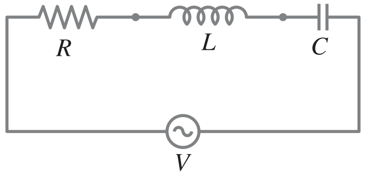


FIGURE 21–43 An *LRC* circuit.

Let us examine a circuit containing all three elements in series: a resistor R, an inductor L, and a capacitor C, Fig. 21–43. If a given circuit contains only two of these elements, we can still use the results of this Section by setting $R = 0$, $X_L = 0$, or $X_C = 0$, as needed. We let V_R, V_L, and V_C represent the voltage across each element at a *given instant* in time; and V_{R0}, V_{L0}, and V_{C0} represent the *maximum* (peak) values of these voltages. The voltage across each of the elements will follow the phase relations we discussed in the previous Section. At any instant the voltage V supplied by the source will be, by Kirchhoff's loop rule,

$$V = V_R + V_L + V_C. \qquad \textbf{(21–13a)}$$

CAUTION

Peak voltages do not add to yield source voltage

Because the various voltages are not in phase, they do not reach their peak values at the same time, so the peak voltage of the source V_0 will *not* equal $V_{R0} + V_{L0} + V_{C0}$.

* Phasor Diagrams

The current in an *LRC* circuit at any instant is the same at all points in the circuit (charge does not pile up in the wires). Thus the currents in each element are in phase with each other, even though the voltages are not. We choose our origin in time ($t = 0$) so that the current I at any time t is

$$I = I_0 \cos 2\pi f t.$$

AC circuits are complicated to analyze. The easiest approach is to use a sort of vector device known as a **phasor diagram**. Arrows (treated like vectors) are drawn in an xy coordinate system to represent each voltage. The length of each arrow represents the magnitude of the peak voltage across each element:

$$V_{R0} = I_0 R, \qquad V_{L0} = I_0 X_L, \qquad \text{and} \qquad V_{C0} = I_0 X_C. \qquad \textbf{(21–13b)}$$

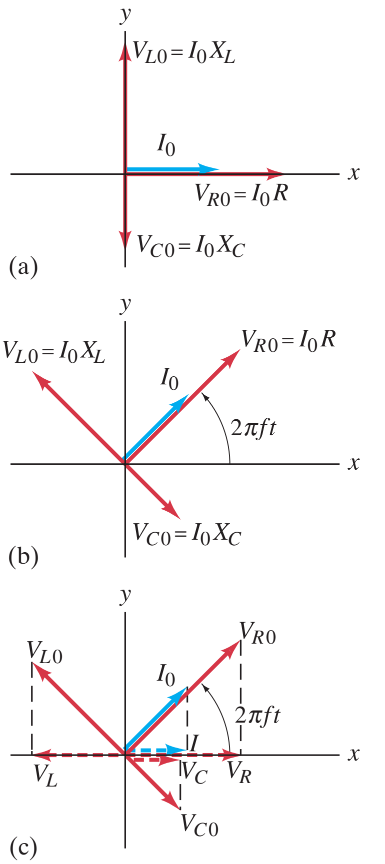


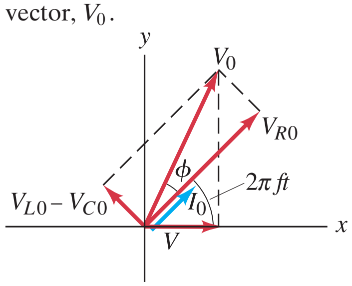
FIGURE 21–44 Phasor diagram for a series *LRC* circuit at (a) $t = 0$, (b) time t later. (c) Projections on the x axis which give I, V_R, V_C, V_L at time t.

V_{R0} is in phase with the current and is initially ($t = 0$) drawn along the positive x axis, as is the current I_0. V_{L0} leads the current by 90°, so it leads V_{R0} by 90° and is initially drawn along the positive y axis. V_{C0} lags the current by 90°, so V_{C0} is drawn initially along the negative y axis. See Fig. 21–44a. If we let the vector diagram rotate counterclockwise at frequency f, we get the diagram shown in Fig. 21–44b; after a time, t, each arrow has rotated through an angle $2\pi f t$. Then the projections of each arrow on the x axis represent the voltages across each element at the instant t, as can be seen in Fig. 21–44c. For example $I = I_0 \cos 2\pi f t$.

The sum of the projections of the three voltage vectors represents the instantaneous voltage across the whole circuit, V. Therefore, the vector sum of these vectors will be the vector that represents the peak source voltage, V_0, as shown in Fig. 21–45 where it is seen that V_0 makes an angle ϕ with I_0 and V_{R0}. As time passes, V_0 rotates with the other vectors, so the instantaneous voltage V (projection of V_0 on the x axis) is (see Fig. 21–45)

$$V = V_0 \cos(2\pi f t + \phi).$$

FIGURE 21–45 Phasor diagram for a series *LRC* circuit showing the sum vector, V_0.



The voltage V across the whole circuit must equal the source voltage (Fig. 21–43). Thus the voltage from the source is out of phase with the current by an angle ϕ.

From this analysis we can now determine the total **impedance** Z of the circuit, which is defined in analogy to resistance and reactance as

$$V_{rms} = I_{rms} Z, \qquad \text{or} \qquad V_0 = I_0 Z. \qquad \textbf{(21–14)}$$

From Fig. 21–45 we see, using the Pythagorean theorem (V_0 is the hypotenuse of a right triangle), that (use Eq. 21–13b)

$$V_0 = \sqrt{V_{R0}^2 + (V_{L0} - V_{C0})^2}$$
$$= I_0\sqrt{R^2 + (X_L - X_C)^2}.$$

Thus, from Eq. 21–14, the total impedance Z is

$$Z = \sqrt{R^2 + (X_L - X_C)^2}. \quad \textbf{(21–15)}$$

Also from Fig. 21–45, we can find the phase angle ϕ between voltage and current:

$$\tan\phi = \frac{V_{L0} - V_{C0}}{V_{R0}} = \frac{I_0(X_L - X_C)}{I_0 R} = \frac{X_L - X_C}{R} \quad \textbf{(21–16a)}$$

and

$$\cos\phi = \frac{V_{R0}}{V_0} = \frac{I_0 R}{I_0 Z} = \frac{R}{Z}. \quad \textbf{(21–16b)}$$

Figure 21–45 was drawn for the case $X_L > X_C$, and the current lags the source voltage by ϕ. When the reverse is true, $X_L < X_C$, then ϕ in Eqs. 21–16 is less than zero, and the current leads the source voltage.

We saw earlier that power is dissipated only by a resistance; none is dissipated by inductance or capacitance. Therefore, the average power is given by $\overline{P} = I_{\rm rms}^2 R$. But from Eq. 21–16b, $R = Z\cos\phi$. Therefore

$$\overline{P} = I_{\rm rms}^2 Z\cos\phi = I_{\rm rms}V_{\rm rms}\cos\phi. \quad \textbf{(21–17)}$$

The factor $\cos\phi$ is referred to as the **power factor** of the circuit.

EXAMPLE 21–15 ***LRC* circuit.** Suppose $R = 25.0\,\Omega$, $L = 30.0\,\text{mH}$, and $C = 12.0\,\mu\text{F}$ in Fig. 21–43, and they are connected in series to a 90.0-V ac (rms) 500-Hz source. Calculate (*a*) the current in the circuit, and (*b*) the voltmeter readings (rms) across each element.

APPROACH To obtain the current, we determine the impedance (Eq. 21–15 plus Eqs. 21–11b and 21–12b), and then use $I_{\rm rms} = V_{\rm rms}/Z$ (Eq. 21–14). Voltage drops across each element are found using Ohm's law or equivalent for each element: $V_R = IR$, $V_L = IX_L$, and $V_C = IX_C$.

SOLUTION (*a*) First, we find the reactance of the inductor and capacitor at $f = 500\,\text{Hz} = 500\,\text{s}^{-1}$:

$$X_L = 2\pi f L = 94.2\,\Omega, \qquad X_C = \frac{1}{2\pi f C} = 26.5\,\Omega.$$

Then the total impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(25.0\,\Omega)^2 + (94.2\,\Omega - 26.5\,\Omega)^2} = 72.2\,\Omega.$$

From the impedance version of Ohm's law, Eq. 21–14,

$$I_{\rm rms} = \frac{V_{\rm rms}}{Z} = \frac{90.0\,\text{V}}{72.2\,\Omega} = 1.25\,\text{A}.$$

(*b*) The rms voltage across each element is

$$(V_R)_{\rm rms} = I_{\rm rms}R = (1.25\,\text{A})(25.0\,\Omega) = 31.2\,\text{V}$$
$$(V_L)_{\rm rms} = I_{\rm rms}X_L = (1.25\,\text{A})(94.2\,\Omega) = 118\,\text{V}$$
$$(V_C)_{\rm rms} = I_{\rm rms}X_C = (1.25\,\text{A})(26.5\,\Omega) = 33.1\,\text{V}.$$

NOTE These voltages do *not* add up to the source voltage, 90.0 V (rms). Indeed, the rms voltage across the inductance *exceeds* the source voltage. This can happen because the different voltages are out of phase with each other: so, at any instant the capacitor's voltage might be negative which compensates for a large positive inductor voltage. The rms voltages, however, are always positive by definition. Although the rms voltages need not add up to the source voltage, the instantaneous voltages at any time must add up to the source voltage at that instant.

CAUTION

Individual peak or rms voltages do NOT add up to source voltage (due to phase differences)

*21–15 Resonance in AC Circuits

The rms current in an LRC series circuit is given by (see Eqs. 21–14, 21–15, 21–11b, and 21–12b):

$$I_{\text{rms}} = \frac{V_{\text{rms}}}{Z} = \frac{V_{\text{rms}}}{\sqrt{R^2 + \left(2\pi fL - \dfrac{1}{2\pi fC}\right)^2}}. \qquad \textbf{(21–18)}$$

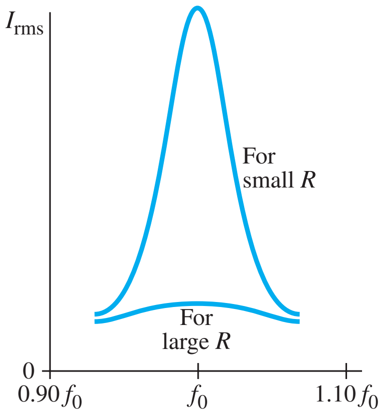


FIGURE 21–46 Current in an LRC circuit as a function of frequency, showing resonance peak at $f = f_0 = 1/(2\pi\sqrt{LC})$.

Because the reactance of inductors and capacitors depends on the frequency f of the source, the current in an LRC circuit depends on frequency. From Eq. 21–18 we see that the current will be maximum at a frequency that satisfies

$$2\pi fL - \frac{1}{2\pi fC} = 0.$$

We solve this for f, and call the solution f_0:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}. \qquad \text{[resonance]} \quad \textbf{(21–19)}$$

When $f = f_0$, the circuit is in **resonance**, and f_0 is the **resonant frequency** of the circuit. At this frequency, $X_C = X_L$, so the impedance is purely resistive. A graph of I_{rms} versus f is shown in Fig. 21–46 for particular values of R, L, and C. For smaller R compared to X_L and X_C, the resonance peak will be higher and sharper.

When R is very small, we speak of an ***LC* circuit**. The energy in an LC circuit oscillates, at frequency f_0, between the inductor and the capacitor, with some being dissipated in R (some resistance is unavoidable). This is called an ***LC* oscillation** or an **electromagnetic oscillation**. Not only does the charge oscillate back and forth, but so does the energy, which oscillates between being stored in the electric field of the capacitor and in the magnetic field of the inductor.

Electric resonance is used in many circuits. Radio and TV sets, for example, use resonant circuits for tuning in a station. Many frequencies reach the circuit from the antenna, but a significant current flows only for frequencies at or near the resonant frequency chosen (the station you want). Either L or C is variable so that different stations can be tuned in (more on this in Chapter 22).

Summary

The **magnetic flux** passing through a loop is equal to the product of the area of the loop times the perpendicular component of the magnetic field:

$$\Phi_B = B_\perp A = BA\cos\theta. \qquad \textbf{(21–1)}$$

If the magnetic flux through a coil of wire changes in time, an emf is induced in the coil. The magnitude of the induced emf equals the time rate of change of the magnetic flux through the loop times the number N of loops in the coil:

$$\mathscr{E} = -N\frac{\Delta\Phi_B}{\Delta t}. \qquad \textbf{(21–2b)}$$

This is **Faraday's law of induction**.

The induced emf can produce a current whose magnetic field opposes the original change in flux (**Lenz's law**).

Faraday's law also tells us that a changing magnetic field produces an electric field; and that a straight wire of length ℓ moving with speed v perpendicular to a magnetic field of strength B has an emf induced between its ends equal to

$$\mathscr{E} = B\ell v. \qquad \textbf{(21–3)}$$

An electric **generator** changes mechanical energy into electric energy. Its operation is based on Faraday's law: a coil of wire is made to rotate uniformly by mechanical means in a magnetic field, and the changing flux through the coil induces a sinusoidal current, which is the output of the generator.

A motor, which operates in the reverse of a generator, acts like a generator in that a **back emf** is induced in its rotating coil. Because this back emf opposes the input voltage, it can act to limit the current in a motor coil. Similarly, a generator acts somewhat like a motor in that a **counter torque** acts on its rotating coil.

A **transformer**, which is a device to change the magnitude of an ac voltage, consists of a primary coil and a secondary coil. The changing flux due to an ac voltage in the primary coil induces an ac voltage in the secondary coil. In a 100% efficient transformer, the ratio of output to input voltages (V_S/V_P) equals the ratio of the number of turns N_S in the secondary to the number N_P in the primary:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}. \qquad \textbf{(21–6)}$$

The ratio of secondary to primary current is in the inverse ratio of turns:

$$\frac{I_S}{I_P} = \frac{N_P}{N_S}. \qquad \textbf{(21–7)}$$

[*Read/write heads for computer hard drives and tape, as well as microphones, ground fault circuit interrupters, and seismographs, are all applications of electromagnetic induction.]

[*A changing current in a coil of wire will produce a changing magnetic field that induces an emf in a second coil placed nearby. The **mutual inductance**, M, is defined by

$$\mathscr{E}_2 = -M\frac{\Delta I_1}{\Delta t}. \qquad \textbf{(21–8)]}$$

[*Within a single coil, the changing B due to a changing current induces an opposing emf, $\mathscr{E}$, so a coil has a **self-inductance** L defined by

$$\mathscr{E} = -L\frac{\Delta I}{\Delta t}. \qquad \textbf{(21–9)]}$$

[*The energy stored in an inductance L carrying current I is given by $U = \frac{1}{2}LI^2$. This energy can be thought of as being stored in the magnetic field of the inductor. The energy density u in any magnetic field B is given by

$$u = \frac{1}{2}\frac{B^2}{\mu_0}. \qquad \textbf{(21–10)]}$$

[*When an inductance L and resistor R are connected in series to a source of emf, V_0, the current rises as

$$I = \frac{V_0}{R}\left(1 - e^{-t/\tau}\right),$$

where $\tau = L/R$ is the **time constant**. If the battery is suddenly switched out of the LR circuit, the current drops exponentially, $I = I_{\text{max}}e^{-t/\tau}$.]

[*Inductive and capacitive **reactance**, X, defined as for resistors, is the proportionality constant between voltage and current (either the rms or peak values). Across an inductor,

$$V = IX_L, \qquad \textbf{(21–11a)}$$

and across a capacitor,

$$V = IX_C. \qquad \textbf{(21–12a)}$$

The reactance of an inductor increases with frequency f,

$$X_L = 2\pi fL, \qquad \textbf{(21–11b)}$$

whereas the reactance of a capacitor decreases with frequency f,

$$X_C = \frac{1}{2\pi fC}. \qquad \textbf{(21–12b)}$$

The current through a resistor is always in phase with the voltage across it, but in an inductor the current lags the voltage by 90°, and in a capacitor the current leads the voltage by 90°.]

[*In an LRC series circuit, the total **impedance** Z is defined by the equivalent of $V = IR$ for resistance, namely,

$$V_0 = I_0 Z \quad \text{or} \quad V_{\text{rms}} = I_{\text{rms}} Z; \qquad \textbf{(21–14)}$$

Z is given by

$$Z = \sqrt{R^2 + \left(X_L - X_C\right)^2}. \qquad \textbf{(21–15)]}$$

[*An LRC series circuit **resonates** at a frequency given by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}. \qquad \textbf{(21–19)}$$

The rms current in the circuit is largest when the applied voltage has a frequency equal to f_0.]

Questions

1. What would be the advantage, in Faraday's experiments (Fig. 21–1), of using coils with many turns?

2. What is the difference between magnetic flux and magnetic field?

3. Suppose you are holding a circular ring of wire in front of you and (*a*) suddenly thrust a magnet, south pole first, away from you toward the center of the circle. Is a current induced in the wire? (*b*) Is a current induced when the magnet is held steady within the ring? (*c*) Is a current induced when you withdraw the magnet? For each yes answer, specify the direction. Explain your answers.

4. (*a*) A wire loop is pulled away from a current-carrying wire (Fig. 21–47). What is the direction of the induced current in the loop: clockwise or counterclockwise? (*b*) What if the wire loop stays fixed as the current I decreases? Explain your answers.

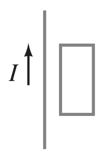


FIGURE 21–47 Question 4.

5. (*a*) If the north pole of a thin flat magnet moves on a table toward a loop also on the table (Fig. 21–48), in what direction is the induced current in the loop? Assume the magnet is the same thickness as the wire. (*b*) What if the magnet is four times thicker than the wire loop? Explain your answers.

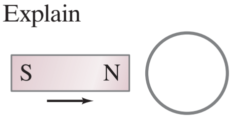


FIGURE 21–48 Question 5.

6. Suppose you are looking along a line through the centers of two circular (but separate) wire loops, one behind the other. A battery is suddenly connected to the front loop, establishing a clockwise current. (*a*) Will a current be induced in the second loop? (*b*) If so, when does this current start? (*c*) When does it stop? (*d*) In what direction is this current? (*e*) Is there a force between the two loops? (*f*) If so, in what direction?

7. The battery mentioned in Question 6 is disconnected. Will a current be induced in the second loop? If so, when does it start and stop? In what direction is this current?

8. In Fig. 21–49, determine the direction of the induced current in resistor R_A (*a*) when coil B is moved toward coil A, (*b*) when coil B is moved away from A, (*c*) when the resistance R_B is increased but the coils remain fixed. Explain your answers.

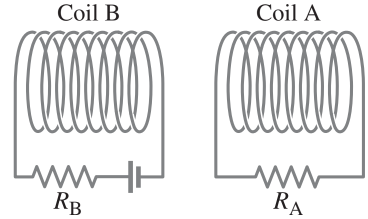


FIGURE 21–49 Question 8.

9. In situations where a small signal must travel over a distance, a *shielded cable* is used in which the signal wire is surrounded by an insulator and then enclosed by a cylindrical conductor (shield) carrying the return current. Why is a "shield" necessary?

10. What is the advantage of placing the two insulated electric wires carrying ac close together or even twisted about each other?

11. Explain why, exactly, the lights may dim briefly when a refrigerator motor starts up. When an electric heater is turned on, the lights may stay dimmed as long as the heater is on. Explain the difference.

12. Use Figs. 21–14 and 21–17 plus the right-hand rules to show why the counter torque in a generator *opposes* the motion.

13. Will an eddy current brake (Fig. 21–20) work on a copper or aluminum wheel, or must the wheel be ferromagnetic? Explain.

14. A bar magnet falling inside a vertical metal tube reaches a terminal velocity even if the tube is evacuated so that there is no air resistance. Explain.

15. It has been proposed that eddy currents be used to help sort solid waste for recycling. The waste is first ground into tiny pieces and iron removed with a magnet. The waste then is allowed to slide down an incline over permanent magnets. How will this aid in the separation of nonferrous metals (Al, Cu, Pb, brass) from nonmetallic materials?

16. The pivoted metal bar with slots in Fig. 21–50 falls much more quickly through a magnetic field than does a solid bar. Explain.

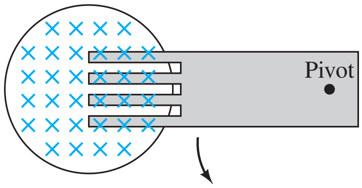


FIGURE 21–50 Question 16.

17. If an aluminum sheet is held between the poles of a large bar magnet, it requires some force to pull it out of the magnetic field even though the sheet is not ferromagnetic and does not touch the pole faces. Explain.

18. A bar magnet is held above the floor and dropped (Fig. 21–51). In case (a), the magnet falls through a wire loop. In case (b), there is nothing between the magnet and the floor. How will the speeds of the magnets compare? Explain.

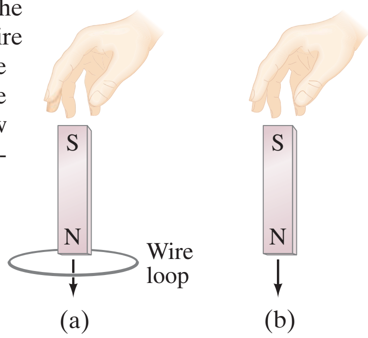


FIGURE 21–51 Question 18 and MisConceptual Question 5.

19. A metal bar, pivoted at one end, oscillates freely in the absence of a magnetic field; but in a magnetic field, its oscillations are quickly damped out. Explain. (This *magnetic damping* is used in a number of practical devices.)

20. An enclosed transformer has four wire leads coming from it. How could you determine the ratio of turns on the two coils without taking the transformer apart? How would you know which wires paired with which?

21. The use of higher-voltage lines in homes—say, 600 V or 1200 V—would reduce energy waste. Why are they not used?

22. A transformer designed for a 120-V ac input will often "burn out" if connected to a 120-V dc source. Explain. [*Hint*: The resistance of the primary coil is usually very low.]

***23.** How would you arrange two flat circular coils so that their mutual inductance was (*a*) greatest, (*b*) least (without separating them by a great distance)? Explain.

***24.** Does the emf of the battery in Fig. 21–37 affect the time needed for the *LR* circuit to reach (*a*) a given fraction of its maximum possible current, (*b*) a given value of current? Explain.

***25.** In an *LRC* circuit, can the rms voltage across (*a*) an inductor, (*b*) a capacitor, be greater than the rms voltage of the ac source? Explain.

***26.** Describe briefly how the frequency of the source emf affects the impedance of (*a*) a pure resistance, (*b*) a pure capacitance, (*c*) a pure inductance, (*d*) an *LRC* circuit near resonance (R small), (*e*) an *LRC* circuit far from resonance (R small).

***27.** Describe how to make the impedance in an *LRC* circuit a minimum.

***28.** An *LRC* resonant circuit is often called an *oscillator* circuit. What is it that oscillates?

***29.** Is the ac current in the inductor always the same as the current in the resistor of an *LRC* circuit? Explain.

MisConceptual Questions

1. A coil rests in the plane of the page while a magnetic field is directed into the page. A clockwise current is induced
(*a*) when the magnetic field gets stronger.
(*b*) when the size of the coil decreases.
(*c*) when the coil is moved sideways across the page.
(*d*) when the magnetic field is tilted so it is no longer perpendicular to the page.

2. A wire loop moves at constant velocity without rotation through a constant magnetic field. The induced current in the loop will be
(*a*) clockwise. (*b*) counterclockwise. (*c*) zero.
(*d*) We need to know the orientation of the loop relative to the magnetic field.

3. A square loop moves to the right from an area where $\vec{\mathbf{B}} = 0$, completely through a region containing a uniform magnetic field directed into the page (Fig. 21–52), and then out to $B = 0$ after point L. A current is induced in the loop
(*a*) only as it passes line J.
(*b*) only as it passes line K.
(*c*) only as it passes line L.
(*d*) as it passes line J or line L.
(*e*) as it passes all three lines.

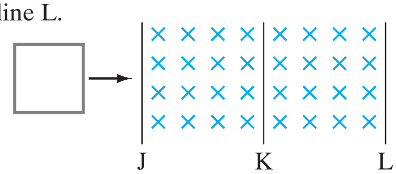


FIGURE 21–52 MisConceptual Question 3.

4. Two loops of wire are moving in the vicinity of a very long straight wire carrying a steady current (Fig. 21–53). Find the direction of the induced current in each loop.

For C:
(*a*) clockwise.
(*b*) counterclockwise.
(*c*) zero.
(*d*) alternating (ac).

For D:
(*a*) clockwise.
(*b*) counterclockwise.
(*c*) zero.
(*d*) alternating (ac).

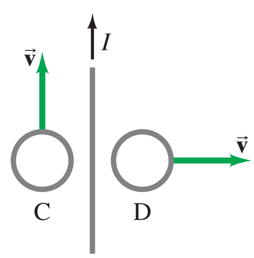


FIGURE 21–53 MisConceptual Question 4.

5. If there is induced current in Question 18 (see Fig. 21–51), wouldn't that cost energy? Where would that energy come from in case (a)?
(*a*) Induced current doesn't need energy.
(*b*) Energy conservation is violated.
(*c*) There is less kinetic energy.
(*d*) There is more gravitational potential energy.

6. A nonconducting plastic hoop is held in a magnetic field that points out of the page (Fig. 21–54). As the strength of the field increases,
(*a*) an induced emf will be produced that causes a clockwise current.
(*b*) an induced emf will be produced that causes a counterclockwise current.
(*c*) an induced emf will be produced but no current.
(*d*) no induced emf will be produced.

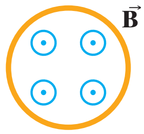


FIGURE 21–54 MisConceptual Question 6.

7. A long straight wire carries a current I as shown in Fig. 21–55. A small loop of wire rests in the plane of the page. Which of the following will *not* induce a current in the loop?
(*a*) Increasing the current in the straight wire.
(*b*) Moving the loop in a direction parallel to the wire.
(*c*) Rotating the loop so that it becomes perpendicular to the plane of the page.
(*d*) Moving the loop farther from the wire without rotating it.
(*e*) Moving the loop farther from the wire while rotating it.

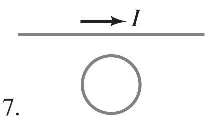


FIGURE 21–55 MisConceptual Question 7.

8. Two separate but nearby coils are mounted along the same axis. A power supply controls the flow of current in the first coil, and thus the magnetic field it produces. The second coil is connected only to an ammeter. The ammeter will indicate that a current is flowing in the second coil
(*a*) whenever a current flows in the first coil.
(*b*) only when a steady current flows in the first coil.
(*c*) only when the current in the first coil changes.
(*d*) only if the second coil is connected to the power supply by rewiring it to be in series with the first coil.

9. When a generator is used to produce electric current, the resulting electric energy originates from which source?
(*a*) The generator's magnetic field.
(*b*) Whatever rotates the generator's axle.
(*c*) The resistance of the generator's coil.
(*d*) Back emf.
(*e*) Empty space.

10. Which of the following will *not* increase a generator's voltage output?
(*a*) Rotating the generator faster.
(*b*) Increasing the area of the coil.
(*c*) Rotating the magnetic field so that it is more closely parallel to the generator's rotation axis.
(*d*) Increasing the magnetic field through the coil.
(*e*) Increasing the number of turns in the coil.

11. Which of the following can a transformer accomplish?
(*a*) Changing voltage but not current.
(*b*) Changing current but not voltage.
(*c*) Changing power.
(*d*) Changing both current and voltage.

12. A laptop computer's charger unit converts 120 V from a wall power outlet to the lower voltage required by the laptop. Inside the charger's plastic case is a diode or rectifier (discussed in Chapter 29) that changes ac to dc plus a
(*a*) battery.
(*b*) motor.
(*c*) generator.
(*d*) transformer.
(*e*) transmission line.

13. Which of the following statements about transformers is false?
(*a*) Transformers work using ac current or dc current.
(*b*) If the current in the secondary is higher, the voltage is lower.
(*c*) If the voltage in the secondary is higher, the current is lower.
(*d*) If no flux is lost, the product of the voltage and the current is the same in the primary and secondary coils.

14. A 10-V, 1.0-A dc current is run through a step-up transformer that has 10 turns on the input side and 20 turns on the output side. What is the output?
(*a*) 10 V, 0.5 A.
(*b*) 20 V, 0.5 A.
(*c*) 20 V, 1 A.
(*d*) 10 V, 1 A.
(*e*) 0 V, 0 A.

15. The alternating electric current at a wall outlet is most commonly produced by
(*a*) a connection to rechargeable batteries.
(*b*) a rotating coil that is immersed in a magnetic field.
(*c*) accelerating electrons between oppositely charged capacitor plates.
(*d*) using an electric motor.
(*e*) alternately heating and cooling a wire.

*16. When you swipe a credit card, the machine sometimes fails to read the card. What can you do differently?
(*a*) Swipe the card more slowly so that the reader has more time to read the magnetic stripe.
(*b*) Swipe the card more quickly so that the induced emf is higher.
(*c*) Swipe the card more quickly so that the induced currents are reduced.
(*d*) Swipe the card more slowly so that the magnetic fields don't change so fast.

*17. Which of the following is true about all series ac circuits?
(*a*) The voltage across any circuit element is a maximum when the current is a maximum in that circuit element.
(*b*) The current at any point in the circuit is always the same as the current at any other point in the circuit.
(*c*) The current in the circuit is a maximum when the source ac voltage is a maximum.
(*d*) Resistors, capacitors, and inductors can all change the phase of the current.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

21–1 to 21–4 Faraday's Law of Induction

1. (I) The magnetic flux through a coil of wire containing two loops changes at a constant rate from −58 Wb to +38 Wb in 0.34 s. What is the emf induced in the coil?

2. (I) The north pole of the magnet in Fig. 21–57 is being inserted into the coil. In which direction is the induced current flowing through resistor R? Explain.

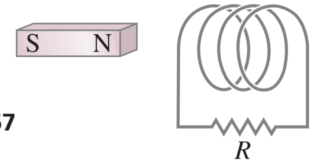


FIGURE 21–57 Problem 2.

3. (I) The rectangular loop in Fig. 21–58 is being pushed to the right, where the magnetic field points inward. In what direction is the induced current? Explain your reasoning.

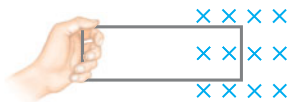


FIGURE 21–58 Problem 3.

4. (I) If the solenoid in Fig. 21–59 is being pulled away from the loop shown, in what direction is the induced current in the loop? Explain.

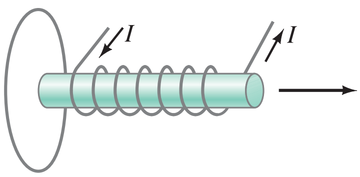


FIGURE 21–59 Problem 4.

5. (II) An 18.5-cm-diameter loop of wire is initially oriented perpendicular to a 1.5-T magnetic field. The loop is rotated so that its plane is parallel to the field direction in 0.20 s. What is the average induced emf in the loop?

6. (II) A fixed 10.8-cm-diameter wire coil is perpendicular to a magnetic field 0.48 T pointing up. In 0.16 s, the field is changed to 0.25 T pointing down. What is the average induced emf in the coil?

7. (II) A 16-cm-diameter circular loop of wire is placed in a 0.50-T magnetic field. (*a*) When the plane of the loop is perpendicular to the field lines, what is the magnetic flux through the loop? (*b*) The plane of the loop is rotated until it makes a 42° angle with the field lines. What is the angle θ in Eq. 21–1 for this situation? (*c*) What is the magnetic flux through the loop at this angle?

8. (II) (*a*) If the resistance of the resistor in Fig. 21–60 is slowly increased, what is the direction of the current induced in the small circular loop inside the larger loop? (*b*) What would it be if the small loop were placed outside the larger one, to the left? Explain your answers.

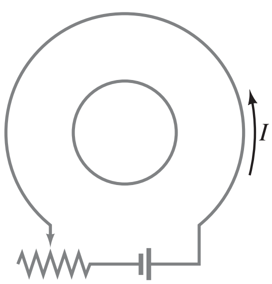


FIGURE 21–60 Problem 8.

9. (II) The moving rod in Fig. 21–11 is 12.0 cm long and is pulled at a speed of 18.0 cm/s. If the magnetic field is 0.800 T, calculate (*a*) the emf developed, and (*b*) the electric field felt by electrons in the rod.

10. (II) A circular loop in the plane of the paper lies in a 0.65-T magnetic field pointing into the paper. The loop's diameter changes from 20.0 cm to 6.0 cm in 0.50 s. What is (*a*) the direction of the induced current, (*b*) the magnitude of the average induced emf, and (*c*) the average induced current if the coil resistance is 2.5 Ω?

11. (II) What is the direction of the induced current in the circular loop due to the current shown in each part of Fig. 21–61? Explain why.

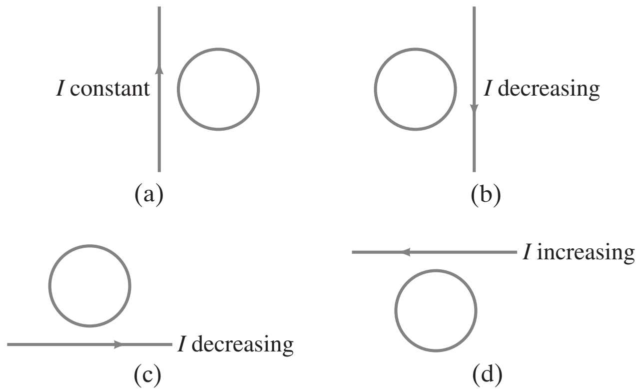


FIGURE 21–61 Problem 11.

12. (II) A 600-turn solenoid, 25 cm long, has a diameter of 2.5 cm. A 14-turn coil is wound tightly around the center of the solenoid. If the current in the solenoid increases uniformly from 0 to 5.0 A in 0.60 s, what will be the induced emf in the short coil during this time?

13. (II) When a car drives through the Earth's magnetic field, an emf is induced in its vertical 55-cm-long radio antenna. If the Earth's field $(5.0 \times 10^{-5}\,\mathrm{T})$ points north with a dip angle of 38°, what is the maximum emf induced in the antenna and which direction(s) will the car be moving to produce this maximum value? The car's speed is 30.0 m/s on a horizontal road.

14. (II) Part of a single rectangular loop of wire with dimensions shown in Fig. 21–62 is situated inside a region of uniform magnetic field of 0.550 T. The total resistance of the loop is 0.230 Ω. Calculate the force required to pull the loop from the field (to the right) at a constant velocity of 3.10 m/s. Neglect gravity.

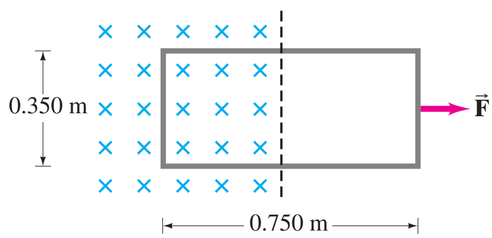


FIGURE 21–62 Problem 14.

15. (II) In order to make the rod of Fig. 21–11a move to the right at speed v, you need to apply an external force on the rod to the right. (*a*) Explain and determine the magnitude of the required force. (*b*) What external power is needed to move the rod? (Do not confuse this external force on the rod with the upward force on the electrons shown in Fig. 21–11b.)

16. (II) In Fig. 21–11, the moving rod has a resistance of 0.25 Ω and moves on rails 20.0 cm apart. The stationary U-shaped conductor has negligible resistance. When a force of 0.350 N is applied to the rod, it moves to the right at a constant speed of 1.50 m/s. What is the magnetic field?

17. (III) In Fig. 21–11, the rod moves with a speed of 1.6 m/s on rails 30.0 cm apart. The rod has a resistance of 2.5 Ω. The magnetic field is 0.35 T, and the resistance of the U-shaped conductor is 21.0 Ω at a given instant. Calculate (*a*) the induced emf, (*b*) the current in the U-shaped conductor, and (*c*) the external force needed to keep the rod's velocity constant at that instant.

18. (III) A 22.0-cm-diameter coil consists of 30 turns of circular copper wire 2.6 mm in diameter. A uniform magnetic field, perpendicular to the plane of the coil, changes at a rate of 8.65×10^{-3} T/s. Determine (*a*) the current in the loop, and (*b*) the rate at which thermal energy is produced.

19. (III) The magnetic field perpendicular to a single 13.2-cm-diameter circular loop of copper wire decreases uniformly from 0.670 T to zero. If the wire is 2.25 mm in diameter, how much charge moves past a point in the coil during this operation?

21–5 Generators

20. (II) The generator of a car idling at 1100 rpm produces 12.7 V. What will the output be at a rotation speed of 2500 rpm, assuming nothing else changes?

21. (II) A 550-loop circular armature coil with a diameter of 8.0 cm rotates at 120 rev/s in a uniform magnetic field of strength 0.55 T. (*a*) What is the rms voltage output of the generator? (*b*) What would you do to the rotation frequency in order to double the rms voltage output?

22. (II) A generator rotates at 85 Hz in a magnetic field of 0.030 T. It has 950 turns and produces an rms voltage of 150 V and an rms current of 70.0 A. (*a*) What is the peak current produced? (*b*) What is the area of each turn of the coil?

23. (III) A simple generator has a square armature 6.0 cm on a side. The armature has 85 turns of 0.59-mm-diameter copper wire and rotates in a 0.65-T magnetic field. The generator is used to power a lightbulb rated at 12.0 V and 25.0 W. At what rate should the generator rotate to provide 12.0 V to the bulb? Consider the resistance of the wire on the armature.

21–6 Back EMF and Torque

24. (I) A motor has an armature resistance of 3.65 Ω. If it draws 8.20 A when running at full speed and connected to a 120-V line, how large is the back emf?

25. (I) The back emf in a motor is 72 V when operating at 1800 rpm. What would be the back emf at 2300 rpm if the magnetic field is unchanged?

26. (II) What will be the current in the motor of Example 21–8 if the load causes it to run at half speed?

21–7 Transformers

[Assume 100% efficiency, unless stated otherwise.]

27. (I) A transformer is designed to change 117 V into 13,500 V, and there are 148 turns in the primary coil. How many turns are in the secondary coil?

28. (I) A transformer has 360 turns in the primary coil and 120 in the secondary coil. What kind of transformer is this, and by what factor does it change the voltage? By what factor does it change the current?

29. (I) A step-up transformer increases 25 V to 120 V. What is the current in the secondary coil as compared to the primary coil?

30. (I) Neon signs require 12 kV for their operation. To operate from a 240-V line, what must be the ratio of secondary to primary turns of the transformer? What would the voltage output be if the transformer were connected in reverse?

31. (II) A model-train transformer plugs into 120-V ac and draws 0.35 A while supplying 6.8 A to the train. (*a*) What voltage is present across the tracks? (*b*) Is the transformer step-up or step-down?

32. (II) The output voltage of a 95-W transformer is 12 V, and the input current is 25 A. (*a*) Is this a step-up or a step-down transformer? (*b*) By what factor is the voltage multiplied?

33. (II) A transformer has 330 primary turns and 1240 secondary turns. The input voltage is 120 V and the output current is 15.0 A. What are the output voltage and input current?

34. (II) If 35 MW of power at 45 kV (rms) arrives at a town from a generator via 4.6-Ω transmission lines, calculate (*a*) the emf at the generator end of the lines, and (*b*) the fraction of the power generated that is wasted in the lines.

35. (II) For the transmission of electric power from power plant to home, as depicted in Fig. 21–25, where the electric power sent by the plant is 100 kW, about how far away could the house be from the power plant before power loss is 50%? Assume the wires have a resistance per unit length of 5×10^{-5} Ω/m.

36. (II) For the electric power transmission system shown in Fig. 21–25, what is the ratio N_S/N_P for (*a*) the step-up transformer, (*b*) the step-down transformer next to the home?

37. (III) Suppose 2.0 MW is to arrive at a large shopping mall over two 0.100-Ω lines. Estimate how much power is saved if the voltage is stepped up from 120 V to 1200 V and then down again, rather than simply transmitting at 120 V. Assume the transformers are each 99% efficient.

38. (III) Design a dc transmission line that can transmit 925 MW of electricity 185 km with only a 2.5% loss. The wires are to be made of aluminum and the voltage is 660 kV.

*21–10 Inductance

*39. (I) If the current in a 160-mH coil changes steadily from 25.0 A to 10.0 A in 350 ms, what is the magnitude of the induced emf?

*40. (I) What is the inductance of a coil if the coil produces an emf of 2.50 V when the current in it changes from −28.0 mA to +31.0 mA in 14.0 ms?

*41. (I) Determine the inductance L of a 0.60-m-long air-filled solenoid 2.9 cm in diameter containing 8500 loops.

*42. (I) How many turns of wire would be required to make a 130-mH inductor out of a 30.0-cm-long air-filled solenoid with a diameter of 5.8 cm?

*43. (II) An air-filled cylindrical inductor has 2600 turns, and it is 2.5 cm in diameter and 28.2 cm long. (*a*) What is its inductance? (*b*) How many turns would you need to generate the same inductance if the core were iron-filled instead? Assume the magnetic permeability of iron is about 1200 times that of free space.

*44. (II) A coil has 2.25-Ω resistance and 112-mH inductance. If the current is 3.00 A and is increasing at a rate of 3.80 A/s, what is the potential difference across the coil at this moment?

***45.** (III) A physics professor wants to demonstrate the large size of the henry unit. On the outside of a 12-cm-diameter plastic hollow tube, she wants to wind an air-filled solenoid with self-inductance of 1.0 H using copper wire with a 0.81-mm diameter. The solenoid is to be tightly wound with each turn touching its neighbor (the wire has a thin insulating layer on its surface so the neighboring turns are not in electrical contact). How long will the plastic tube need to be and how many kilometers of copper wire will be required? What will be the resistance of this solenoid?

***46.** (III) A long thin solenoid of length ℓ and cross-sectional area A contains N_1 closely packed turns of wire. Wrapped tightly around it is an insulated coil of N_2 turns, Fig. 21–63. Assume all the flux from coil 1 (the solenoid) passes through coil 2, and calculate the mutual inductance.

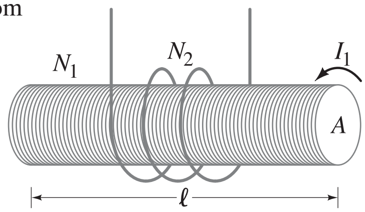


FIGURE 21–63 Problem 46.

*21–11 Magnetic Energy Storage

***47.** (I) The magnetic field inside an air-filled solenoid 36 cm long and 2.0 cm in diameter is 0.72 T. Approximately how much energy is stored in this field?

***48.** (II) At $t = 0$, the current through a 45.0-mH inductor is 50.0 mA and is increasing at the rate of 115 mA/s. What is the initial energy stored in the inductor, and how long does it take for the energy to increase by a factor of 5.0 from the initial value?

***49.** (II) Assuming the Earth's magnetic field averages about 0.50×10^{-4} T near Earth's surface, estimate the total energy stored in this field in the first 10 km above Earth's surface.

*21–12 *LR* Circuit

***50.** (II) It takes 2.56 ms for the current in an *LR* circuit to increase from zero to 0.75 its maximum value. Determine (*a*) the time constant of the circuit, (*b*) the resistance of the circuit if $L = 31.0$ mH.

***51.** (II) How many time constants does it take for the potential difference across the resistor in an *LR* circuit like that in Fig. 21–37 to drop to 2.5% of its original value, after the switch is moved to the upper position, removing V_0 from the circuit?

***52.** (III) Determine $\Delta I/\Delta t$ at $t = 0$ (when the battery is connected) for the *LR* circuit of Fig. 21–37 and show that if I continued to increase at this rate, it would reach its maximum value in one time constant.

***53.** (III) After how many time constants does the current in Fig. 21–37 reach within (*a*) 10%, (*b*) 1.0%, and (*c*) 0.1% of its maximum value?

*21–13 AC Circuits and Reactance

***54.** (I) What is the reactance of a 6.20-μF capacitor at a frequency of (*a*) 60.0 Hz, (*b*) 1.00 MHz?

***55.** (I) At what frequency will a 32.0-mH inductor have a reactance of 660 Ω?

***56.** (I) At what frequency will a 2.40-μF capacitor have a reactance of 6.10 kΩ?

***57.** (II) Calculate the reactance of, and rms current in, a 260-mH radio coil connected to a 240-V (rms) 10.0-kHz ac line. Ignore resistance.

***58.** (II) An inductance coil operates at 240 V and 60.0 Hz. It draws 12.2 A. What is the coil's inductance?

***59.** (II) (*a*) What is the reactance of a well-insulated 0.030-μF capacitor connected to a 2.0-kV (rms) 720-Hz line? (*b*) What will be the peak value of the current?

*21–14 *LRC* Circuits

***60.** (II) For a 120-V rms 60-Hz voltage, an rms current of 70 mA passing through the human body for 1.0 s could be lethal. What must be the impedance of the body for this to occur?

***61.** (II) A 36-kΩ resistor is in series with a 55-mH inductor and an ac source. Calculate the impedance of the circuit if the source frequency is (*a*) 50 Hz, and (*b*) 3.0×10^4 Hz.

***62.** (II) A 3.5-kΩ resistor and a 3.0-μF capacitor are connected in series to an ac source. Calculate the impedance of the circuit if the source frequency is (*a*) 60 Hz, and (*b*) 60,000 Hz.

***63.** (II) Determine the resistance of a coil if its impedance is 235 Ω and its reactance is 115 Ω.

***64.** (II) Determine the total impedance, phase angle, and rms current in an *LRC* circuit connected to a 10.0-kHz, 725-V (rms) source if $L = 28.0$ mH, $R = 8.70$ kΩ, and $C = 6250$ pF.

***65.** (II) An ac voltage source is connected in series with a 1.0-μF capacitor and a 650-Ω resistor. Using a digital ac voltmeter, the amplitude of the voltage source is measured to be 4.0 V rms, while the voltages across the resistor and across the capacitor are found to be 3.0 V rms and 2.7 V rms, respectively. Determine the frequency of the ac voltage source. Why is the voltage measured across the voltage source not equal to the sum of the voltages measured across the resistor and across the capacitor?

***66.** (III) (*a*) What is the rms current in an *LR* circuit when a 60.0-Hz 120-V rms ac voltage is applied, where $R = 2.80$ kΩ and $L = 350$ mH? (*b*) What is the phase angle between voltage and current? (*c*) How much power is dissipated? (*d*) What are the rms voltage readings across R and L?

***67.** (III) (*a*) What is the rms current in an *RC* circuit if $R = 6.60$ kΩ, $C = 1.80$ μF, and the rms applied voltage is 120 V at 60.0 Hz? (*b*) What is the phase angle between voltage and current? (*c*) What are the voltmeter readings across R and C?

***68.** (III) Suppose circuit B in Fig. 21–42a consists of a resistance $R = 520$ Ω. The filter capacitor has capacitance $C = 1.2$ μF. Will this capacitor act to eliminate 60-Hz ac but pass a high-frequency signal of frequency 6.0 kHz? To check this, determine the voltage drop across R for a 130-mV signal of frequency (*a*) 60 Hz; (*b*) 6.0 kHz.

*21–15 Resonance in AC Circuits

***69.** (I) A 3500-pF capacitor is connected in series to a 55.0-μH coil of resistance 4.00 Ω. What is the resonant frequency of this circuit?

***70.** (II) The variable capacitor in the tuner of an AM radio has a capacitance of 2800 pF when the radio is tuned to a station at 580 kHz. (*a*) What must be the capacitance for a station at 1600 kHz? (*b*) What is the inductance (assumed constant)?

***71.** (II) An *LRC* circuit has $L = 14.8$ mH and $R = 4.10$ Ω. (*a*) What value must C have to produce resonance at 3600 Hz? (*b*) What will be the maximum current at resonance if the peak external voltage is 150 V?

*72. (III) A resonant circuit using a 260-nF capacitor is to resonate at 18.0 kHz. The air-core inductor is to be a solenoid with closely packed coils made from 12.0 m of insulated wire 1.1 mm in diameter. How many loops will the inductor contain?

*73. (III) A 2200-pF capacitor is charged to 120 V and then quickly connected to an inductor. The frequency of oscillation is observed to be 19 kHz. Determine (*a*) the inductance, (*b*) the peak value of the current, and (*c*) the maximum energy stored in the magnetic field of the inductor.

General Problems

74. Suppose you are looking at two wire loops in the plane of the page as shown in Fig. 21–64. When switch S is closed in the left-hand coil, (*a*) what is the direction of the induced current in the other loop? (*b*) What is the situation after a "long" time? (*c*) What is the direction of the induced current in the right-hand loop if that loop is quickly pulled horizontally to the right? (*d*) Suppose the right-hand loop also has a switch like the left-hand loop. The switch in the left-hand loop has been closed a long time when the switch in the right-hand loop is closed. What happens in this case? Explain each answer.

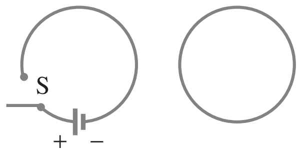


FIGURE 21–64 Problem 74.

75. A square loop 24.0 cm on a side has a resistance of 6.10 Ω. It is initially in a 0.665-T magnetic field, with its plane perpendicular to $\vec{\mathbf{B}}$, but is removed from the field in 40.0 ms. Calculate the electric energy dissipated in this process.

76. A high-intensity desk lamp is rated at 45 W but requires only 12 V. It contains a transformer that converts 120-V household voltage. (*a*) Is the transformer step-up or step-down? (*b*) What is the current in the secondary coil when the lamp is on? (*c*) What is the current in the primary coil? (*d*) What is the resistance of the bulb when on?

77. A flashlight can be made that is powered by the induced current from a magnet moving through a coil of wire. The coil and magnet are inside a plastic tube that can be shaken causing the magnet to move back and forth through the coil. Assume the magnet has a maximum field strength of 0.05 T. Make reasonable assumptions and specify the size of the coil and the number of turns necessary to light a standard 1-watt, 3-V flashlight bulb.

78. Conceptual Example 21–9 states that an overloaded motor may burn out due to high currents. Suppose you have a blender with an internal resistance of 3.0 Ω. (*a*) At 120 V, what is the initial current through the blender? (*b*) The blender is rated at 2.0 A for continuous use. What is the back emf of the blender? (*c*) At what rate is heat dissipated in the blender during normal use? (*d*) If the blender jams and stops turning, at what rate is heat dissipated in the motor coils?

79. Power is generated at 24 kV at a generating plant located 56 km from a town that requires 55 MW of power at 12 kV. Two transmission lines from the plant to the town each have a resistance of 0.10 Ω/km. What should the output voltage of the transformer at the generating plant be for an overall transmission efficiency of 98.5%, assuming a perfect transformer?

80. The primary windings of a transformer which has an 88% efficiency are connected to 110-V ac. The secondary windings are connected across a 2.4-Ω, 75-W lightbulb. (*a*) Calculate the current through the primary windings of the transformer. (*b*) Calculate the ratio of the number of primary windings of the transformer to the number of secondary windings of the transformer.

81. A pair of power transmission lines each have a 0.95-Ω resistance and carry 740 A over 9.0 km. If the rms input voltage is 42 kV, calculate (*a*) the voltage at the other end, (*b*) the power input, (*c*) power loss in the lines, and (*d*) the power output.

82. Two resistanceless rails rest 32 cm apart on a 6.0° ramp. They are joined at the bottom by a 0.60-Ω resistor. At the top a copper bar of mass 0.040 kg (ignore its resistance) is laid across the rails. Assuming a vertical 0.45-T magnetic field, what is the terminal (steady) velocity of the bar as it slides frictionlessly down the rails?

83. Show that the power loss in transmission lines, P_{L}, is given by $P_{\mathrm{L}} = (P_{\mathrm{T}})^2 R_{\mathrm{L}}/V^2$, where P_{T} is the power transmitted to the user, V is the delivered voltage, and R_{L} is the resistance of the power lines.

84. A coil with 190 turns, a radius of 5.0 cm, and a resistance of 12 Ω surrounds a solenoid with 230 turns/cm and a radius of 4.5 cm (Fig. 21–65). The current in the solenoid changes at a constant rate from 0 to 2.0 A in 0.10 s. Calculate the magnitude and direction of the induced current in the outer coil.

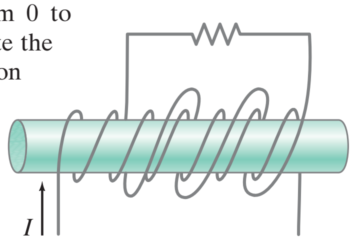


FIGURE 21–65 Problem 84.

85. A certain electronic device needs to be protected against sudden surges in current. In particular, after the power is turned on, the current should rise no more than 7.5 mA in the first 120 μs. The device has resistance 120 Ω and is designed to operate at 55 mA. How would you protect this device?

86. A 35-turn 12.5-cm-diameter coil is placed between the pole pieces of an electromagnet. When the electromagnet is turned on, the flux through the coil changes, inducing an emf. At what rate (in T/s) must the magnetic field change if the emf is to be 120 V?

87. Calculate the peak output voltage of a simple generator whose square armature windings are 6.60 cm on a side; the armature contains 125 loops and rotates in a field of 0.200 T at a rate of 120 rev/s.

*88. Typical large values for electric and magnetic fields attained in laboratories are about 1.0×10^4 V/m and 2.0 T. (*a*) Determine the energy density for each field and compare. (*b*) What magnitude electric field would be needed to produce the same energy density as the 2.0-T magnetic field?

*89. Determine the inductance L of the primary of a transformer whose input is 220 V at 60.0 Hz if the current drawn is 6.3 A. Assume no current in the secondary.

*90. A 130-mH coil whose resistance is 15.8 Ω is connected to a capacitor C and a 1360-Hz source voltage. If the current and voltage are to be in phase, what value must C have?

*91. The wire of a tightly wound solenoid is unwound and used to make another tightly wound solenoid of twice the diameter. By what factor does the inductance change?

*92. The **Q factor** of a resonant ac circuit (Section 21–15) can be defined as the ratio of the voltage across the capacitor (or inductor) to the voltage across the resistor, at resonance. The larger the Q factor, the sharper the resonance curve will be and the sharper the tuning. (*a*) Show that the Q factor is given by the equation $Q = (1/R)\sqrt{L/C}$. (*b*) At a resonant frequency $f_0 = 1.0\,\text{MHz}$, what must be the values of L and R to produce a Q factor of 650? Assume that $C = 0.010\,\mu\text{F}$.

Search and Learn

1. (*a*) Sections 19–7 and 21–9 discuss conditions when and where it is especially important to have ground fault circuit interrupters (GFCIs) installed. What is it about those places that makes "touching ground" especially risky? (*b*) Describe how a GFCI works and compare to fuses and circuit breakers (see also Section 18–6).

2. While demonstrating Faraday's law to her class, a physics professor inadvertently moves the gold ring on her finger from a location where a 0.68-T magnetic field points along her finger to a zero-field location in 45 ms. The 1.5-cm-diameter ring has a resistance and mass of 55 $\mu\Omega$ and 15 g, respectively. (*a*) Estimate the thermal energy produced in the ring due to the flow of induced current. (*b*) Find the temperature rise of the ring, assuming all of the thermal energy produced goes into increasing the ring's temperature. The specific heat of gold is 129 J/kg·C°.

3. A small electric car overcomes a 250-N friction force when traveling 35 km/h. The electric motor is powered by ten 12-V batteries connected in series and is coupled directly to the wheels whose diameters are 58 cm. The 290 armature coils are rectangular, 12 cm by 15 cm, and rotate in a 0.65-T magnetic field. (*a*) How much current does the motor draw to produce the required torque? (*b*) What is the back emf? (*c*) How much power is dissipated in the coils? (*d*) What percent of the input power is used to drive the car? [*Hint*: Check Sections 6–10, 18–5, 20–9, 20–10, and 21–6.]

4. Explain the advantage of using ac rather than dc current when electric power needs to be transported long distances. (See Section 21–7.)

5. A power line carrying a sinusoidally varying current with frequency $f = 60\,\text{Hz}$ and peak value $I_0 = 155\,\text{A}$ runs at a height of 7.0 m across a farmer's land (Fig. 21–66). The farmer constructs a vertical 2.0-m-high 2000-turn rectangular wire coil below the power line. The farmer hopes to use the induced voltage in this coil to power 120-V electrical equipment, which requires a sinusoidally varying voltage with frequency $f = 60\,\text{Hz}$ and peak value $V_0 = 170\,\text{V}$. Estimate the length ℓ of the coil needed. Would this be stealing? [*Hint*: Consider ΔB over one-quarter of a cycle $(\frac{1}{240}\,\text{s})$. See Sections 20–5 and 18–7.]

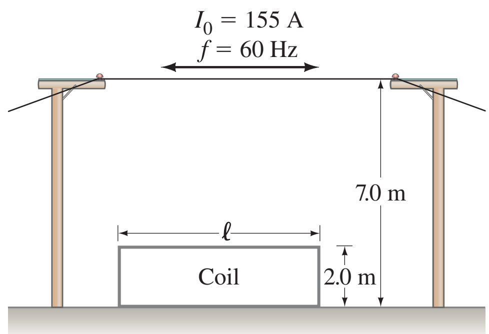


FIGURE 21–66 Search and Learn 5.

6. A **ballistic galvanometer** is a device that measures the total charge Q that passes through it in a short time. It is connected to a **search coil** that measures B (also called a **flip coil**) which is a small coil with N turns, each of cross-sectional area A. The flip coil is placed in the magnetic field to be measured with its face perpendicular to the field. It is then quickly rotated 180° about a diameter. Show that the total charge Q that flows in the induced current during this short "flip" time is proportional to the magnetic field B. In particular, show that

$$B = \frac{QR}{2NA}$$

where R is the total resistance of the circuit including the coil and ballistic galvanometer which measures charge Q.

ANSWERS TO EXERCISES

A: (*e*).
B: (*a*) Counterclockwise; (*b*) clockwise; (*c*) zero; (*d*) counterclockwise.
C: Clockwise (conventional current counterclockwise).
D: (*a*) Increase (brighter); (*b*) yes; resists more (counter torque).
E: 10 turns.
F: From Eq. 21–11b, the higher the frequency the lower the reactance, so in (*a*) more high frequency current flows to circuit B. In (*b*) higher frequencies pass to ground whereas lower frequencies pass more easily to circuit B.