26 AC Electricity

Transmission lines carry alternating current at voltages that can exceed 500,000 V. Why are high voltages used? And why can birds perch safely on high-voltage wires?

LOOKING AHEAD ➤

The goal of Chapter 26 is to understand and apply basic principles of AC electricity, electricity transmission, and household electricity.

Transformers

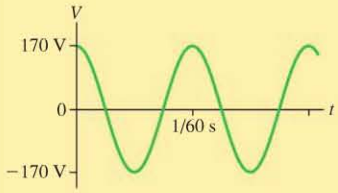
Two coils of wire wrapped around an iron core makes a **transformer,** a device that can change the voltage of AC electricity.

You likely have several portable devices that charge up or run off power packs. These power packs use transformers, converting the 120 V of the wall outlet to the lower voltage needed by electronic devices.

Looking Back ◀
25.3–25.4 Lenz's law and Faraday's law

AC Electricity

We've said that normal household electricity is 120 V, but that's not quite true. The actual voltage oscillates 60 times a second with a peak of approximately 170 V. We'll see that 120 V is what's called the *root-mean-square voltage*. The oscillating voltage causes the current to alternate directions, so we know this as AC, or **alternating current,** electricity.



AC Circuits

Many common devices make use of AC circuits. We can understand AC circuits by extending our knowledge of DC circuits.

The trackpad on a laptop computer uses a network of AC capacitor circuits to determine the position of your fingertip.

Turning your radio tuning dial adjusts the resonant frequency of an AC oscillation circuit.

Looking Back ◀
14.1 and 14.6–14.7 Simple harmonic motion, damped oscillations, and resonance
21.7 Capacitors
23.2 Fundamentals of circuit analysis

Electricity Transmission

The wires that transmit electricity across large distances—the grid—do so at very high voltage. We'll see why this is so.

Transformers in your neighborhood change the locally transmitted high-voltage electricity to a more modest voltage that is safe to use in your home.

Household Electricity and Electrical Safety

The electric nature of your nervous system means that modest electric shocks can be dangerous. You'll learn about household electricity and the safety features built in.

GFI circuits, which detect potentially dangerous electric leakages, provide additional protection at bathroom and kitchen outlets.

26.1 Alternating Current

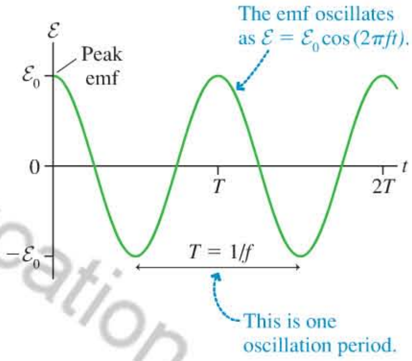
LED minilights flash on and off 60 times a second.

A battery creates a constant emf. In a battery-powered flashlight, the bulb carries a constant current and glows with a steady light. The electricity distributed to homes in your neighborhood is different. The picture on the right is a long-exposure photo of a string of LED minilights swung through the air. Each bulb appears as a series of dashes because each bulb in the string flashes on and off 60 times each second. This isn't a special property of the bulbs, but of the electricity that runs them. Household electricity does not have a constant emf; it has a sinusoidal variation that causes the light output of the bulbs to vary as well, although the resulting flicker is too rapid to notice under normal circumstances.

In Chapter 25 we saw that an electrical generator—whether powered by steam, water, or wind—works by rotating a coil of wire in a magnetic field. The steady rotation of the coil causes the emf and the induced current in the coil to oscillate sinusoidally, alternately positive and then negative. This oscillation forces the charges to flow first in one direction and then, a half cycle later, in the other—an **alternating current,** abbreviated as AC. (If the emf is constant and the current is always in the same direction, we call the electricity *direct current,* abbreviated as DC.) The electricity from power outlets in your house is *AC electricity,* with an emf oscillating at a frequency of 60 Hz. Audio, radio, television, computer, and telecommunication equipment also make extensive use of AC circuits, with frequencies ranging from approximately 10^2 Hz in audio circuits to approximately 10^9 Hz in cell phones.

The instantaneous emf of an AC voltage source, shown graphically in **FIGURE 26.1**, can be written as

FIGURE 26.1 The emf of an AC voltage source.



$$\mathcal{E} = \mathcal{E}_0 \cos(2\pi f t) = \mathcal{E}_0 \cos\left(\frac{2\pi t}{T}\right) \qquad (26.1)$$

Emf of an AC voltage source

where $\mathcal{E}_0$ is the peak or maximum emf (recall that the units of emf are volts), T is the period of oscillation (in s), and $f = 1/T$ is the oscillation frequency (in cycles per second, or Hz).

Resistor Circuits

In Chapter 23 you learned to analyze a circuit in terms of the current I and potential difference ΔV. Now, because the current and voltage are oscillating, we will use a lowercase i to represent the *instantaneous* current through a circuit element, the value of the current at a particular instant of time. Similarly, we will use a lowercase v for the circuit element's instantaneous voltage.

FIGURE 26.2 The instantaneous current through a resistor.

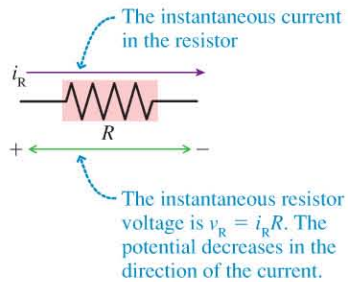


FIGURE 26.2 shows the instantaneous current i_R through a resistor R. The potential difference across the resistor, which we call the *resistor voltage* v_R, is given by Ohm's law:

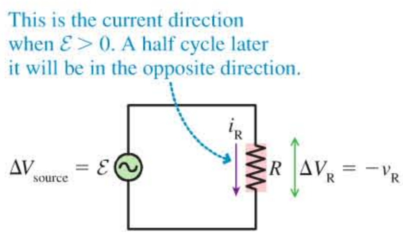
$$v_R = i_R R \qquad (26.2)$$

FIGURE 26.3 shows a resistor R connected across an AC emf $\mathcal{E}$. The circuit symbol for an AC generator is −⊙−. We can analyze this circuit in exactly the same way we analyzed a DC resistor circuit. Kirchhoff's loop law says that the sum of all the potential differences around a closed path is zero so we can write:

$$\sum \Delta V = \Delta V_{source} + \Delta V_R = \mathcal{E} - v_R = 0 \qquad (26.3)$$

The minus sign appears, just as it did in the equation for a DC circuit, because the potential *decreases* when we travel through a resistor in the direction of the current. Thus we find from the loop law that $v_R = \mathcal{E} = \mathcal{E}_0 \cos(2\pi f t)$. This isn't surprising because the resistor is connected directly across the terminals of the emf.

FIGURE 26.3 An AC resistor circuit.



Because the resistor voltage is a sinusoidal voltage at frequency f, it is useful to write

$$v_R = V_R \cos(2\pi f t) \tag{26.4}$$

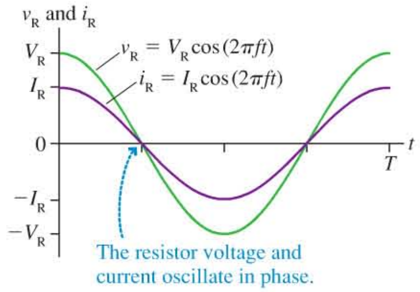
In this equation V_R is the peak or maximum voltage, the amplitude of the sinusoidally varying voltage. You can see that $V_R = \mathcal{E}_0$ in the single-resistor circuit of Figure 26.3. Thus the current through the resistor is

$$i_R = \frac{v_R}{R} = \frac{V_R \cos(2\pi f t)}{R} = I_R \cos(2\pi f t) \tag{26.5}$$

where $I_R = V_R/R$ is the peak current.

NOTE ▶ It is important to understand the distinction between instantaneous and peak quantities. The instantaneous current i_R, for example, is a quantity that is changing with time according to Equation 26.5. The peak current I_R is the maximum value that the instantaneous current reaches. The instantaneous current oscillates between $+I_R$ and $-I_R$. ◀

FIGURE 26.4 Graph of the current through and voltage across a resistor.



The resistor's instantaneous current and voltage are *in phase,* both oscillating as $\cos(2\pi f t)$. FIGURE 26.4 shows the voltage and the current simultaneously on a graph. The fact that the peak current I_R is drawn as being less than V_R has no significance. Current and voltage are measured in different units, so in a graph like this you can't compare the value of one to the value of the other. Showing the two different quantities on a single graph—a tactic that can be misleading if you're not careful—simply illustrates that they oscillate *in phase:* **The current is at its maximum value when the voltage is at its maximum, and the current is at its minimum value when the voltage is at its minimum.**

AC Power in Resistors

In Chapter 23 you learned that the power dissipated by a resistor is $P = I\Delta V_R = I^2R$. In an AC circuit, the resistor current i_R and voltage v_R are constantly changing, as we saw in Figure 26.4, so the instantaneous power loss $p = i_R v_R = i_R^2 R$ (note the lowercase p) is constantly changing as well. We can use Equations 26.4 and 26.5 to write this instantaneous power as

$$p = i_R^2 R = [I_R \cos(2\pi f t)]^2 R = I_R^2 R[\cos(2\pi f t)]^2 \tag{26.6}$$

FIGURE 26.5 The instantaneous power loss in a resistor.

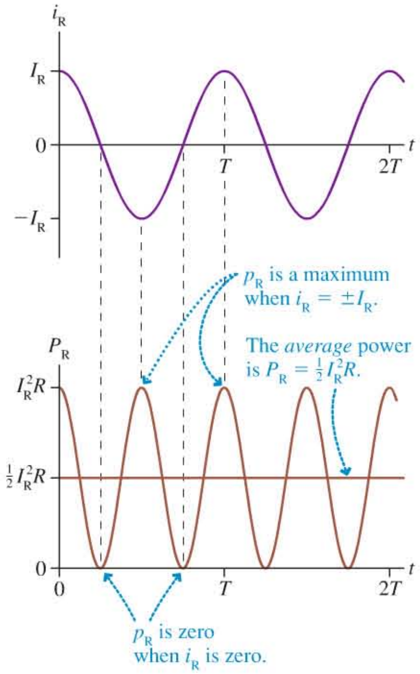


FIGURE 26.5 shows the instantaneous power graphically. You can see that, because the cosine is squared, the power oscillates *twice* during every cycle of the emf: The energy dissipation peaks both when $i_R = I_R$ and when $i_R = -I_R$. The energy dissipation doesn't depend on the current's direction through the resistor.

The current in a household lightbulb reverses direction 120 times per second (twice per cycle), so the power reaches a maximum 120 times a second. But the hot filament of the bulb glows steadily, so it makes more sense to pay attention to the *average power* than the instantaneous power. Figure 26.5 shows the **average power** P_R is related to the peak power as follows:

$$P_R = \frac{1}{2} I_R^2 R \tag{26.7}$$

In a DC circuit, the power is $P_R = I^2R$. It's conventional to write Equation 26.7 in a form that resembles this DC expression. We do so by writing

$$P_R = \left(\frac{I_R}{\sqrt{2}}\right)^2 R = (I_{rms})^2 R \tag{26.8}$$

where the quantity

$$I_{rms} = \frac{I_R}{\sqrt{2}} \tag{26.9}$$

is called the **root-mean-square current,** or rms current, I_{rms}. We saw this idea before in Chapter 12, where we introduced the rms speed of molecules in a gas.

Using the rms current allows us to compare Equation 26.8 directly to the energy dissipated by a resistor in a DC circuit: $P = I^2R$. The average power loss of a resistor in an AC circuit with $I_{rms} = 1$ A is the same as in a DC circuit with $I = 1$ A. **As far as average power is concerned, an rms current is equivalent to a DC current.**

Similarly, we can define the root-mean-square voltage:

$$V_{rms} = \frac{V_R}{\sqrt{2}} \tag{26.10}$$

The resistor's average power loss can be written in terms of the rms quantities as

$$P_R = (I_{rms})^2 R = \frac{(V_{rms})^2}{R} = I_{rms}V_{rms} \tag{26.11}$$

Average power loss in a resistor

The "120 V" on this lightbulb is its operating rms voltage. The "100 W" is its average power dissipation at this voltage.

NOTE ► As long as we work with rms voltages and currents, all the expressions you learned for DC power carry over to AC power. ◄

AC voltages and currents are usually given as rms values. For instance, we've noted that household lamps and appliances in the United States operate at the 120 V present at wall outlets. This voltage is the rms value $\mathcal{E}_{rms}$; the peak voltage is higher by a factor of $\sqrt{2}$, so $\mathcal{E}_0 = 170$ V.

EXAMPLE 26.1 The resistance and current of a toaster

The hot wire in a toaster dissipates 580 W when plugged into a 120 V outlet.

a. What is the wire's resistance?
b. What are the rms and peak currents through the wire?

PREPARE The filament has resistance R. It dissipates 580 W when there's an rms voltage of 120 V across it. We can solve Equation 26.11 for R and then use Equations 26.11 and 26.9 to find the rms current and the peak current.

SOLVE

a. We can rearrange Equation 26.11 to find the resistance from the rms voltage and the average power:

$$R = \frac{(V_{rms})^2}{P_R} = \frac{(120\text{ V})^2}{580\text{ W}} = 25\ \Omega$$

b. A second rearrangement of Equation 26.11 allows us to find the current in terms of the power and the resistance, both of which are known:

$$I_{rms} = \sqrt{\frac{P_R}{R}} = \sqrt{\frac{580\text{ W}}{25\ \Omega}} = 4.8\text{ A}$$

From Equation 26.9, the peak current is

$$I_R = \sqrt{2}I_{rms} = \sqrt{2}(4.8\text{ A}) = 6.8\text{ A}$$

ASSESS We can do a quick check on our work by calculating the power for the rated voltage and computed current:

$$P_R = I_{rms}V_{rms} = (4.8\text{ A})(120\text{ V}) = 580\text{ W}$$

This agrees with the value given in the problem statement, giving us confidence in our solution.

STOP TO THINK 26.1 An AC current with a peak value of 1.0 A passes through bulb A. A DC current of 1.0 A passes through an identical bulb B. Which bulb is brighter?

A. Bulb A. B. Bulb B. C. Both bulbs are equally bright.

26.2 AC Electricity and Transformers

Your cell phone runs at about 3.5 V. To charge it up from a wall outlet at $V_{rms} = 120$ V requires the use of a **transformer,** a device that takes an *alternating* voltage as an input and produces either a higher or lower voltage as its output. As

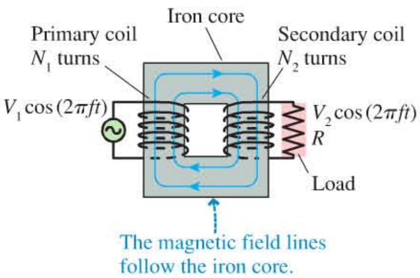
Your cell phone charger incorporates a transformer that provides the necessary voltage reduction.

we'll see, the operation of a transformer is based on the emf produced by changing magnetic fields, so the input must be AC electricity.

Transformer Operation

FIGURE 26.6 shows a simplified version of a transformer, consisting of two coils of wire wrapped on a single iron core. The left coil is called the **primary coil** (or simply the *primary*). It has N_1 turns of wire connected to an AC voltage of amplitude V_1. This AC voltage creates an alternating current. The current in the coil creates a magnetic field that magnetizes the iron of the core to produce a much stronger net field—and a large flux through the primary coil. The field lines tend to follow the iron core, as shown in the figure, so nearly all of the flux from the left primary coil also goes through the right coil of wire, which has N_2 turns and is called the **secondary coil** (or the *secondary*). The current in the primary coil is an alternating current, so it creates an oscillating magnetic field in the iron core; the changing magnetic field means that there is a changing flux in the secondary coil. This changing flux induces an emf, an AC voltage of amplitude V_2, in the secondary coil. To complete the picture, we connect this emf to a resistor R, which we call the *load*. Current in this resistor will dissipate power.

FIGURE 26.6 A transformer.



The point of a transformer is to change the voltage, so we need to define how the voltage V_2 at the secondary is related to the voltage V_1 at the primary. Suppose at some instant of time the instantaneous current through the primary is i_1. This current creates a magnetic flux Φ through the primary coil. This flux is changing, because i_1 is changing, and the change induces an emf across the coil. According to Faraday's law (Equation 25.12), the instantaneous voltage v_1 across the N_1 turns of the primary coil is

$$v_1 = \mathcal{E}_1 = N_1\frac{\Delta\Phi}{\Delta t} \tag{26.12}$$

In an **ideal transformer,** all of the flux is "guided" by the iron core through the secondary coil. Consequently, the rate at which the flux changes through the secondary coil is also $\Delta\Phi/\Delta t$. This changing flux induces an emf across the secondary coil given by

$$v_2 = \mathcal{E}_2 = N_2\frac{\Delta\Phi}{\Delta t} \tag{26.13}$$

Because $\Delta\Phi/\Delta t$ is the same in Equations 26.12 and 26.13, we can write

$$\frac{v_1}{v_2} = \frac{N_1}{N_2} \tag{26.14}$$

Equation 26.14 gives the ratio of the instantaneous voltages. This equation also applies at the instant at which these voltages are at their peak values V_1 and V_2, and the rms voltages are related to these peak values by a factor of $1/\sqrt{2}$. We can thus relate the peak and rms voltages of the primary and secondary coils:

$$V_2 = \frac{N_2}{N_1}V_1 \qquad \text{and} \qquad (V_2)_{\text{rms}} = \frac{N_2}{N_1}(V_1)_{\text{rms}} \tag{26.15}$$

Transformer voltages for primary and secondary coils with N_1 and N_2 turns

◀ **Getting a charge** There is no direct electrical contact between the primary and secondary coils in a transformer; the energy is carried from one coil to the other by the magnetic field. This makes it possible to charge devices that are completely sealed, with no external electrical contacts, such as the electric toothbrush shown. A primary coil in the base creates an alternating magnetic field that induces an alternating emf in a secondary coil in the brush's handle. This emf, after conversion to DC, is used to charge the toothbrush's battery.

Depending on the ratio N_2/N_1, the voltage V_2 across the load can be transformed to a higher or a lower voltage than V_1. A *step-up transformer,* with $N_2 > N_1$, increases the voltage, while a *step-down transformer,* with $N_2 < N_1$, lowers the voltage.

Equation 26.15 relates the voltage at a transformer's secondary to the voltage at its primary. We can also relate the *currents* in the secondary and primary by considering energy conservation. If a transformer is connected to a load that draws an rms current $(I_2)_{\text{rms}}$ from the secondary, the average power supplied to the load by the transformer, given by Equation 26.11, is

$$P_2 = (V_2)_{\text{rms}}\,(I_2)_{\text{rms}}$$

The primary coil draws a current $(I_1)_{\text{rms}}$ from the voltage source to which it's connected. This source provides power

$$P_1 = (V_1)_{\text{rms}}\,(I_1)_{\text{rms}}$$

to the transformer.

We'll assume that our ideal transformer has no loss of electric energy, so $P_1 = P_2$, or $(V_1)_{\text{rms}}(I_1)_{\text{rms}} = (V_2)_{\text{rms}}(I_2)_{\text{rms}}$. Thus we have

$$(I_2)_{\text{rms}} = \frac{(V_1)_{\text{rms}}}{(V_2)_{\text{rms}}}(I_1)_{\text{rms}} = \frac{N_1}{N_2}(I_1)_{\text{rms}} \tag{26.16}$$

Transformer currents for primary and secondary coils with N_1 and N_2 turns

Here we used Equation 26.15 to relate the ratio of voltages to the ratio of turns. Comparing Equations 26.15 and 26.16, you can see that a step-up transformer *raises* voltage but *lowers* current. This must be the case in order to conserve energy. Similarly, a step-down transformer *lowers* the voltage but *raises* the current. We've made some assumptions about the ideal transformer in completing this derivation. Real transformers come quite close to this ideal, so you can use the above equations for computations on real transformers.

EXAMPLE 26.2 Analyzing a step-up transformer

A book light has a 1.4 W, 4.8 V bulb that is powered by a transformer connected to a 120 V electric outlet. The secondary coil of the transformer has 20 turns of wire. How many turns does the primary coil have? What is the current in the primary coil?

PREPARE The circuit is the basic transformer circuit of Figure 26.6; the load is the bulb. We know the voltages of the primary and the secondary, so we can compute the turns in the primary coil using Equation 26.15. We know the voltage and the power of the bulb, so we can find the current in the bulb—the current in the secondary—which we can then use to compute the current in the primary using Equation 26.16.

SOLVE The bulb is rated at 4.8 V; this is the rms voltage at the secondary, so $(V_2)_{\text{rms}} = 4.8$ V. The power outlet has the usual $(V_1)_{\text{rms}} = 120$ V, so we can rearrange Equation 26.15 to find

$$N_1 = N_2\frac{(V_1)_{\text{rms}}}{(V_2)_{\text{rms}}} = (20\text{ turns})\left(\frac{120\text{ V}}{4.8\text{ V}}\right) = 500\text{ turns}$$

The bulb connected to the secondary dissipates 1.4 W at 4.8 V; this is an rms voltage, so the rms current in the secondary is

$$(I_2)_{\text{rms}} = \frac{P_2}{(V_2)_{\text{rms}}} = \frac{1.4\text{ W}}{4.8\text{ V}} = 0.29\text{ A}$$

We can then rearrange Equation 26.16 to find the rms current in the primary:

$$(I_1)_{\text{rms}} = (I_2)_{\text{rms}}\frac{N_2}{N_1} = (0.29\text{ A})\frac{20}{500} = 0.012\text{ A}$$

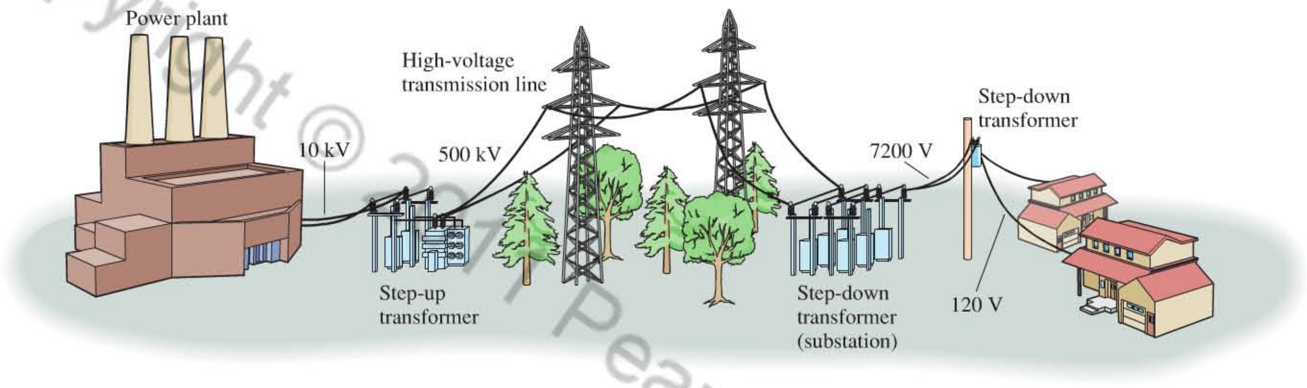
ASSESS We can check our results by looking at the power supplied by the wall outlet. This is $P_1 = (120\text{ V})(0.012\text{ A}) = 1.4$ W, the same as the power dissipated by the bulb, as must be the case because we've assumed the transformer is ideal.

Power Transmission

Long-distance electrical transmission lines run at very high voltages—up to 1,000,000 volts! This is a higher voltage than the output of an electrical generator, and a much higher voltage than you use in your home. Why is power transmitted at such high voltages? In a word: efficiency.

To understand why power transmission is more efficient at high voltages, let's look at the power transmitted and the power lost for the simple model of a power plant, transmission line, and city shown in FIGURE 26.7. To provide power to the city, the power plant generates an emf $\mathcal{E}_{rms}$ and delivers a current I_{rms} through the wires. If the power plant is 50 km from the city, a fairly typical distance, the 100 km of wire used in the transmission line (to the city and back) has a resistance of about 7 Ω.

FIGURE 26.7 How electric power is delivered from the power plant to a city.



A modest-sized city of 100,000 inhabitants uses approximately 120 MW of electric power—this is the power that must be transmitted. To transmit this power at the outlet voltage of 120 V, we can use Equation 26.11 to find that the current in the transmission line would have to be

$$I_{rms} = \frac{P_{city}}{V_{rms}} = \frac{120 \times 10^6 \text{ W}}{120 \text{ V}} = 10^6 \text{ A}$$

This is an extraordinarily large current, which would incur correspondingly large losses. We know the resistance of the wire; passing this 10^6 A through a transmission line with 7 Ω of resistance would transform a good deal of energy to thermal energy in the resistance of the wire. The power "lost" would be

$$P_{lost} = (I_{rms})^2 R = (10^6 \text{ A})^2 (7 \text{ } \Omega) = 7 \times 10^{12} \text{ W}$$

In other words, 60,000 times more power would be lost in the transmission line than is used by the city! This is clearly impractical and unrealistic.

But suppose we use a step-up transformer at the power plant to boost the voltage to 500,000 V. To transmit 120 MW of power at 500 kV requires a current of only

$$I_{rms} = \frac{P_{city}}{V_{rms}} = \frac{120 \times 10^6 \text{ W}}{500{,}000 \text{ V}} = 240 \text{ A}$$

This is still a large current, but one that can be handled by typical aluminum transmission line cables with a diameter of roughly 1 inch. At this current, the power loss in the 7 Ω resistance of the transmission line is $P_{lost} = (I_{rms})^2 R = 400$ kW. This is less than 1% of the power used by the city, an acceptable loss. Because power loss in the transmission lines depends on the *square* of the current, higher voltages and thus smaller currents provide a huge improvement in efficiency.

Using electricity at 500,000 V at the outlet is clearly dangerous and impractical. Step-down transformers at the city lower the voltage to the usual 120 V. Only AC electricity can use transformers to change voltages and currents for long-distance power transmission. This is the primary reason we use AC electricity in our homes and not DC.

26.3 Household Electricity

The electricity in your home can be understood using the techniques of circuit analysis we've developed, but we need to add one more concept. So far we've only dealt with potential differences. Although we are free to choose the zero point of potential anywhere that is convenient, our analysis of circuits has not suggested any need to establish a zero point. Potential differences are all we have needed.

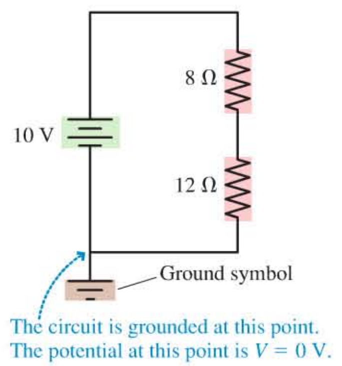
Difficulties can begin to arise, however, if you want to connect two different circuits together. Perhaps you would like to connect your CD player to your amplifier or connect your computer monitor to the computer itself. Incompatibilities can arise unless all the circuits to be connected have a common reference point for the potential. This is the reason for having an electric *ground*.

Getting Grounded

You learned previously that the earth itself is a conductor. Suppose we have two circuits. If we connect one point of each circuit to the earth by an ideal wire, then both circuits have a common reference point. A circuit connected to the earth in this way is said to be **grounded.** In practice, we also agree to call the potential of the earth $V_{\text{earth}} = 0\text{ V}$. FIGURE 26.8 shows a circuit with a ground connection. Under normal circumstances, the ground connection does not carry any current because it is not part of a complete circuit. In this case, it does not alter the behavior of the circuit.

Grounding serves two functions. First, it provides a common reference potential so that different circuits or instruments can be correctly interconnected. Second, it is an important safety feature. As we will see in the next section, a current to ground can quickly open a circuit breaker if an electric appliance malfunctions.

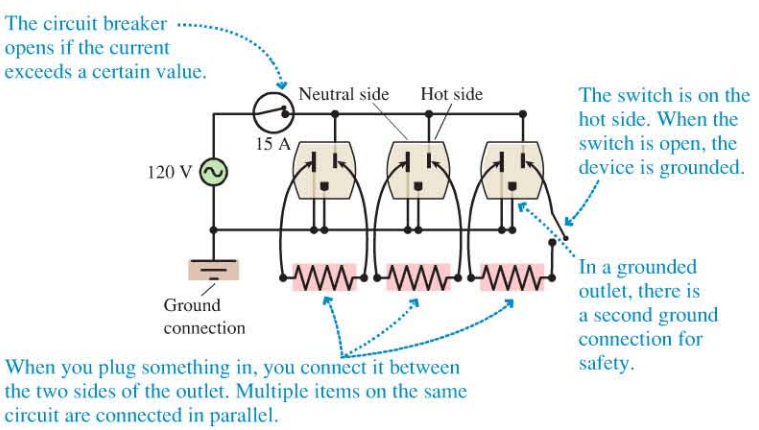
FIGURE 26.8 A grounded circuit.



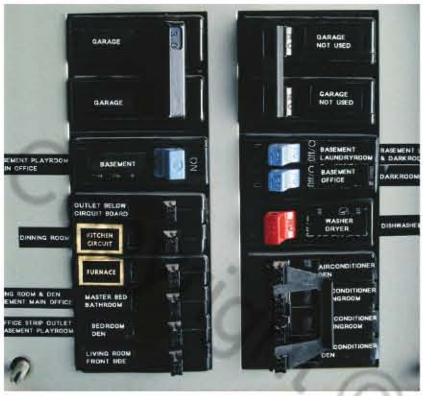
Electric Outlets Are Grounded Parallel Circuits

FIGURE 26.9 shows a circuit diagram for the outlets in your house. The 120 V electric supply is provided by the power company. It is transmitted to outlets throughout your house by wires in the walls. One terminal of the electric supply is grounded; we call this the **neutral** side. The other side is at a varying potential; we call this the **hot** side. Each electric outlet has two slots, one connected to the hot side and one connected to the neutral side. When you insert a plug into an electric outlet, the prongs of the plug connect to the two terminals of the electric supply. The device you've plugged in completes a circuit between the two terminals, the potential difference across the device leads to a current, and the device turns on.

FIGURE 26.9 Multiple outlets on one circuit.



The multiple outlets in a room or area of your house are connected in parallel so that each works when the others are not being used. Because the outlets on a single circuit are in parallel, when you plug in another device, the total current in the circuit increases. This can create a problem; although the wires in your walls are good



A typical circuit breaker panel. Each breaker corresponds to a different circuit in the house.

conductors, they aren't ideal. The wires have a small resistance and heat up when carrying a current. If there is too much current, the wires could get hot enough to cause a fire.

The circuits in your house are protected with circuit breakers to limit the current in each circuit. A circuit breaker consists of a switch and an ammeter that measures the current in the circuit. If the ammeter measures too much current (typically $I_{\text{rms}} \geq 15$ A), it sends a signal to open the switch to disconnect the circuit. You have probably had the experience of having a circuit breaker "trip" if you have too many things plugged in. To keep the problem from recurring, you must reduce the current in the circuit. Some things need to be turned off, unplugged, or moved to a different circuit.

Grounding of household circuits provides an important reference potential, as noted above, but the main reason for grounding is safety. The two slots in a standard outlet are different sizes; the neutral slot is a bit larger. Most electric devices are fitted with plugs that can be inserted into an outlet in only one orientation. A lamp, for instance, will almost certainly have this sort of plug. This is an important safety feature; when you turn the lamp off, the switch disconnects the hot wire, not the neutral wire. The lamp is then grounded, and thus safe, when it is switched off.

The round hole in a standard electric outlet is a second ground connection that serves a second safety function. If a device has a metal case, whether it's a microwave oven or an electric drill, the case will likely be connected to the ground. If a wire comes loose inside the device and contacts the metal case, a person touching the case could get a shock. But if the case is grounded, its potential is always 0 V and it is always safe to touch. In addition, a hot wire touching the grounded case would be a short circuit, causing a sudden very large current that would trip the circuit breaker, disconnecting the hot wire and preventing any danger. If you plug something in and the circuit breaker trips, the device likely has an electrical fault and should be repaired or discarded.

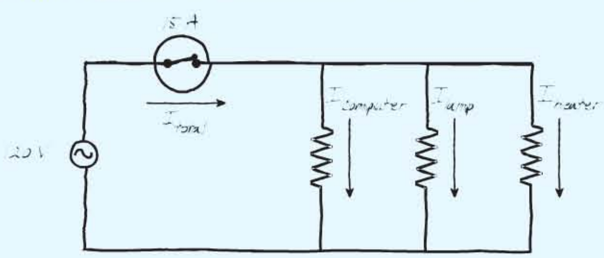
◀ A two-prong "polarized" plug has one large prong and one small one. When plugged into a standard outlet, the large prong is grounded. A three-prong plug has a round pin that makes a second ground connection.

EXAMPLE 26.3 **Will the circuit breaker open?**

A circuit in a student's room has a 15 A circuit breaker. One evening, she plugs in a computer (240 W), a lamp (with two 60 W bulbs), and a space heater (1200 W). Will this be enough to trip the circuit breaker?

PREPARE We start by sketching the circuit, as in **FIGURE 26.10**. Because the three devices are in the same circuit, they are connected in parallel. We can model each of them as a resistor.

FIGURE 26.10 The circuit with the circuit breaker.



SOLVE The current in the circuit is the sum of the currents in the individual devices:

$$(I_{\text{total}})_{\text{rms}} = (I_{\text{computer}})_{\text{rms}} + (I_{\text{lamp}})_{\text{rms}} + (I_{\text{heater}})_{\text{rms}}$$

Equation 26.11 gives the power as the rms current times the rms voltage, so the current in each device is the power divided by the rms voltage:

$$(I_{\text{total}})_{\text{rms}} = \frac{240\text{ W}}{120\text{ V}} + \frac{120\text{ W}}{120\text{ V}} + \frac{1200\text{ W}}{120\text{ V}} = 13\text{ A}$$

This is almost but not quite enough to trip the circuit breaker.

ASSESS Generally all of the outlets in one room (and perhaps the lights as well) are on the same circuit. You can see that it would be quite easy to plug in enough devices to trip the circuit breaker.

Kilowatt Hours

The product of watts and seconds is joules, the SI unit of energy. However, your local electric company prefers to use a different unit, called *kilowatt hours,* to measure the energy you use each month.

A device in your home that consumes P kW of electricity for Δt hours has used $P\Delta t$ kilowatt hours of energy, abbreviated kWh. For example, suppose you run a 1500 W electric water heater for 10 hours. The energy used in kWh is $(1.5 \text{ kW})(10 \text{ hr}) = 15 \text{ kWh}$.

Despite the rather unusual name, a kilowatt hour is a unit of energy, as it is a power multiplied by a time. The conversion between kWh and J is

$$1.00 \text{ kWh} = (1.00 \times 10^3 \text{ W})(3600 \text{ s}) = 3.60 \times 10^6 \text{ J}$$

Your monthly electric bill specifies the number of kilowatt hours you used last month. This is the amount of energy that the electric company delivered to you, via an electric current, and that you transformed into light and thermal energy inside your home.

The electric meter on the side of your house or apartment records the kilowatt hours of electricity you use each month.

EXAMPLE 26.4 **Computing the cost of electric energy**

A typical electric space heater draws an rms current of 12.5 A on its highest setting. If electricity costs 10¢ per kilowatt hour (an approximate national average), how much does it cost to run the heater for 2 hours?

SOLVE The power dissipated by the heater is

$$P = V_{\text{rms}} I_{\text{rms}} = (120 \text{ V})(12.5 \text{ A}) = 1500 \text{ W} = 1.5 \text{ kW}$$

In 2 hours, the energy used is

$$\mathcal{E} = (1.5 \text{ kW})(2.0 \text{ hr}) = 3.0 \text{ kWh}$$

At 10¢ per kWh, the cost is 30¢.

FIGURE 26.11 High voltages are not necessarily dangerous.

26.4 Biological Effects and Electrical Safety

You can handle an ordinary 9 V battery without the slightest danger, but the 120 volts from an electric outlet can lead to a nasty shock. Yet the girl in **FIGURE 26.11** is safely touching a Van de Graaff generator at a potential of 400,000 V. What makes electricity either safe or dangerous?

The relative safety of electric sources isn't governed by the voltage but by the current. Current—the flow of charges through the body—is what produces physiological effects and damage because it mimics nerve impulses and causes muscles to involuntarily contract.

Higher voltages are generally more dangerous than lower voltages because they tend to produce larger currents, but the amount of current also depends on resistance and on the ability of the voltage source to deliver current. The Van de Graaff generator in Figure 26.11 is at a high potential with respect to the ground, but the girl is standing on an insulating platform. The high resistance of the platform means that very little current is passing through her to the ground; she won't feel a thing. Even if she touches a grounded object, the current will be modest—the total charge on the generator is quite small, so a dangerous current simply isn't possible. You can get a much worse shock from a 120 V household circuit because it is capable of providing a much larger current.

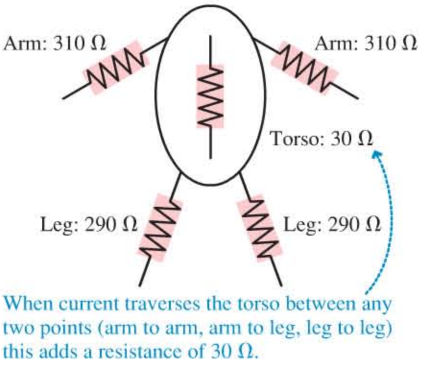
Table 26.1 lists approximate values of current that produce different physiological effects. Currents through the chest cavity are particularly dangerous because they can interfere with respiration and the proper rhythm of the heart. An AC current larger than 100 mA can induce fibrillation of the heart, in which it beats in a rapid, chaotic, uncontrolled fashion.

To calculate likely currents through the body, we model the body as several connected resistors, as shown in **FIGURE 26.12**. (These are averages; there is significant individual variation around these values.) Because of its high saltwater content, the resistance of the interior of the body is fairly low. But current must pass through the skin before getting inside the body, and the skin generally has a fairly high

TABLE 26.1 Physiological effects of currents passing through the body

Physiological effect	AC current (rms) (mA)	DC current (mA)
Threshold of sensation	1	3
Paralysis of respiratory muscles	15	60
Heart fibrillation, likely fatal	> 100	> 500

FIGURE 26.12 Resistance model of the body.



resistance. If you touch a wire with the dry skin of a finger, the skin's resistance might be greater than 1 MΩ. Moist skin and larger contact areas can reduce the skin's resistance to less than 10 kΩ. **The skin's resistance is in series with the resistances shown in Figure 26.12.**

EXAMPLE 26.5 Is the worker in danger?

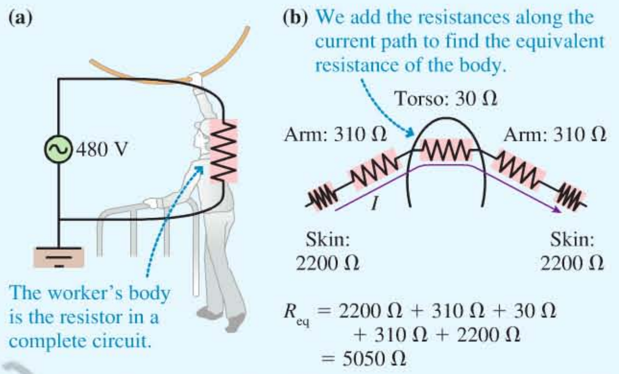
A worker in a plant grabs a bare wire that he does not know is connected to a 480 V AC supply. His other hand is holding a grounded metal railing. The skin resistance of each of his hands, in full contact with a conductor, is 2200 Ω. He will receive a shock. Will it be large enough to be dangerous?

PREPARE We can draw a circuit model for this situation as in FIGURE 26.13a; the worker's body completes a circuit between two points at a potential difference of 480 V. The current will depend on this potential difference and the resistance of his body, including the resistance of the skin.

SOLVE Following the model of Figure 26.12, the current path goes through the skin of one hand, up one arm, across the torso, down the other arm, and through the skin of the other hand, as in FIGURE 26.13b. The equivalent resistance of the series combination is 5050 Ω, so the AC current through his body is

$$I = \frac{\Delta V}{R_{eq}} = \frac{480\ \text{V}}{5050\ \Omega} = 95\ \text{mA}$$

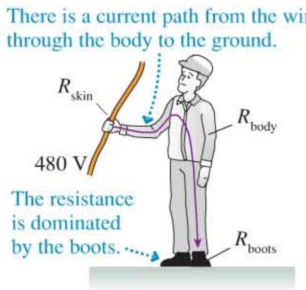
FIGURE 26.13 A circuit model for the worker.



From Table 26.1 we see that this is a very dangerous, possibly fatal, current.

ASSESS The voltage is high and the resistance relatively low, so it's no surprise to find a dangerous level of current.

FIGURE 26.14 Wearing electrically insulating boots increases resistance.



Because of the danger of electrocution, workers who might accidentally contact electric lines wear protective clothing. The soles of boots designed to protect against electric shock have a resistance of 10 MΩ or more. Suppose a worker wearing such boots touches a live wire at 480 V, as shown in FIGURE 26.14. The resistance of the current path through the body is now dominated by the resistance of the boots, which is much larger than the resistance of his body and skin. Assuming 10 MΩ for the resistance of the soles of the boots, the current passing through the worker's body is only

$$I = \frac{\Delta V}{R_{eq}} \approx \frac{\Delta V}{R_{boots}} = \frac{480\ \text{V}}{10\ \text{M}\Omega} = 48\ \mu\text{A}$$

In this case, the worker will be fine. Because the current is much less than the threshold for sensation, he won't even feel a shock!

The current in these examples was due to a potential difference between the hands or between a hand and the feet. How about the birds sitting on the wire at the start of the chapter? How are they able to perch on the high-voltage wire? The wire is at an elevated potential with respect to the ground, but there is no complete circuit—the birds have both feet on the same wire. Each foot is at a high potential, but there is only a very small potential *difference* between the feet due to the potential decrease along the wire, too small to produce any noticeable effect. If a bird touched the wire and a grounded pole, or two neighboring wires, the result would be very different.

◀ **The lightning crouch** You don't need to be hit by lightning to be hurt by lightning. When lightning strikes the ground, a tremendous amount of charge flows outward, implying a large electric field along the ground. If you are standing with your feet separated by a large distance d, a large potential difference $\Delta V = Ed$ will develop between your feet, causing a potentially dangerous current to flow up one leg and down the other. If you're caught outdoors in a lightning storm and can't get to safety, experts recommend that you assume the crouched position shown in the photo. By placing your feet as close together as possible and lifting your heels off the ground, you can minimize the potential difference and thus the current due to a nearby lightning strike.

GFI Circuits

If you are standing in good electrical contact with the ground, you are grounded. If you then accidentally touch a hot wire with your hand, a dangerous current could pass through you to ground. In kitchens and bathrooms, where grounding on damp floors is a good possibility, building codes require *ground fault interrupter* outlets, abbreviated GFI. Some devices, such as hair dryers, are generally constructed with a GFI in the power cord.

GFI outlets have a built-in sensing circuit that compares the currents in the hot and neutral wires of the outlet. In normal operation, all the current coming in through the hot wire passes through the device and then back out through the neutral wire, so the currents in the hot and neutral wires should always be equal. If the current in the hot wire does *not* equal the current in the neutral wire, some current from the hot wire is finding an alternative path to ground—perhaps through a person. This is a *ground fault,* and the GFI disconnects the circuit. GFIs are set to trip at current differences of about 5 mA—large enough to feel, but not large enough to be dangerous.

TRY IT YOURSELF

Testing GFI circuits You can test a GFI circuit by pressing the black "Test" button. This creates an electrical connection between the hot wire and the ground connection, so the currents in the hot and neutral wires will not be equal. You should hear a click as the circuit disconnects. You can then reset the outlet by pressing the red button. If an outlet does not respond like this, it should be replaced.

26.5 Capacitor Circuits

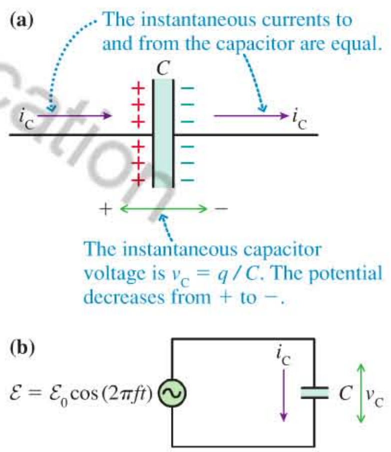
In Chapter 23 we analyzed the one-time charging or discharging of a capacitor in an *RC* circuit. In this chapter we will look at capacitors in circuits with an AC source of emf that repeatedly charges and discharges the capacitor.

FIGURE 26.15a shows a current i_C charging a capacitor with capacitance C. The instantaneous capacitor voltage is $v_C = q/C$, where $\pm q$ is the charge on the two capacitor plates at this instant of time. **FIGURE 26.15b**, where capacitance C is connected across an AC source of emf $\mathcal{E}$, is the most basic capacitor circuit. The capacitor is in parallel with the source, so the capacitor voltage equals the emf: $v_C = \mathcal{E} = \mathcal{E}_0\cos(2\pi ft)$. It is useful to write

$$v_C = V_C\cos(2\pi ft) \tag{26.17}$$

where V_C is the peak or maximum voltage across the capacitor. $V_C = \mathcal{E}_0$ in this single-capacitor circuit.

FIGURE 26.15 An AC capacitor circuit.



Charge flows to and from the capacitor plates but not through the gap between the plates. But the charges $\pm q$ on the opposite plates are always of equal magnitude, so the currents into and out of the capacitor must be equal. We can find the current i_C by considering how the charge q on the capacitor varies with time. In **FIGURE 26.16a** on the next page we have plotted the oscillating voltage v_C across the capacitor. Because the charge and the capacitor voltage are directly proportional, with $q = Cv_C$, the graph of q, shown in **FIGURE 26.16b**, looks like the graph of v_C. We say that the charge is *in phase* with the voltage.

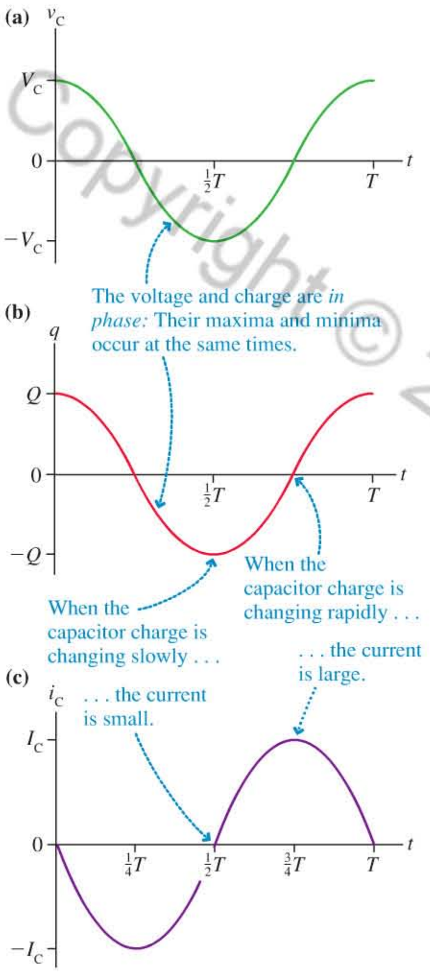
In Chapter 22, we defined current to be $\Delta q/\Delta t$. The capacitor current, i_C, will thus be related to the charge on the capacitor by

$$i_C = \frac{\Delta q}{\Delta t}$$

The main factor determining i_C is Δq, the *change* of charge during a time interval Δt, not the amount of charge q. As the figure shows, when the current is large, the charge on the capacitor is changing rapidly, which makes sense. But these times of large current and rapid change occur when the voltage on the capacitor is small. The maximum current doesn't occur at the same time as the maximum voltage.

A capacitor's voltage and current are *not* in phase, as they were for a resistor. You can see from Figure 26.16 that the current peaks at $\frac{3}{4}$ T, one-quarter period *before* the voltage peaks. We say that **the AC current through a capacitor *leads* the capacitor voltage.**

FIGURE 26.16 Voltage, charge, and current graphs for a capacitor in an AC circuit.



Capacitive Reactance

The phase of the current is not the whole story. We would like to know its peak value, which we can also determine from $i_C = \Delta q/\Delta t$. Because $q = Cv_C$, this can also be written as

$$i_C = C\frac{\Delta v_C}{\Delta t} \tag{26.18}$$

Let's now reason by analogy. In Chapter 14 the position of a simple harmonic oscillator was given by $x = A\cos(2\pi ft)$. Further, the oscillator's velocity $v = \Delta x/\Delta t$ was found to be $x = -v_{max}\sin(2\pi ft)$, with a maximum or peak value $v_{max} = 2\pi fA$. Here we have an oscillating voltage $v_C = V_C\cos(2\pi ft)$, analogous to position, and we need to find the quantity $\Delta v_C/\Delta t$, analogous to velocity. Thus $\Delta v_C/\Delta t$ must have a maximum or peak value $(\Delta v_C/\Delta t)_{max} = 2\pi fV_C$.

The peak capacitor current I_C occurs when $\Delta v_C/\Delta t$ is maximum, so the peak current is

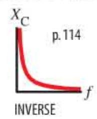
$$I_C = C(2\pi fV_C) = (2\pi fC)V_C \tag{26.19}$$

For a resistor, the peak current and voltage are related through Ohm's law:

$$I_R = \frac{V_R}{R}$$

We can write Equation 26.19 in a form similar to Ohm's law if we define the **capacitive reactance** X_C to be

$$X_C = \frac{1}{2\pi fC} \tag{26.20}$$



With this definition of capacitive reactance, Equation 26.19 becomes

$$I_C = \frac{V_C}{X_C} \quad \text{or} \quad V_C = I_CX_C \tag{26.21}$$

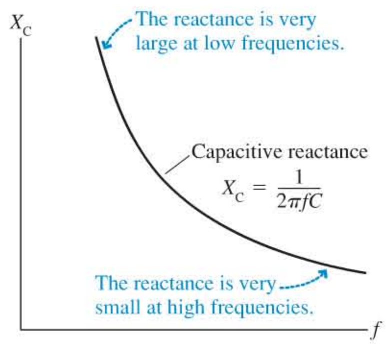
Peak current through or voltage across a capacitor

The units of reactance, like those of resistance, are ohms.

NOTE ► Reactance relates the *peak* voltage V_C and current I_C. It does *not* relate the *instantaneous* capacitor voltage and current because they are out of phase; that is, $v_C \neq i_CX_C$. ◄

A resistor's resistance R is independent of the frequency of the emf. In contrast, as FIGURE 26.17 shows, a capacitor's reactance X_C depends inversely on the frequency. The reactance becomes very large at low frequencies (i.e., the capacitor is a large impediment to current). The reactance decreases as the frequency increases until, at very high frequencies, $X_C \approx 0$ and the capacitor begins to act like an ideal wire.

FIGURE 26.17 The capacitive reactance as a function of frequency.



Replacing a mouse Under the surface of a laptop's trackpad is an array of tiny capacitors. When you touch the pad, your finger's high dielectric constant (it's largely water) changes the capacitance of nearby capacitors. This alters the current in these capacitor circuits, telling the computer the location of your finger. Try touching a trackpad with the eraser end of a pencil. The dielectric constant of the eraser will likely be too small to make an effect.

EXAMPLE 26.6 Finding the capacitive reactance

What is the capacitive reactance of a 0.100 μF capacitor at a 100 Hz audio frequency and at a 100 MHz FM-radio frequency?

SOLVE At 100 Hz,

$$X_C (\text{at } 100\text{ Hz}) = \frac{1}{2\pi f C} = \frac{1}{2\pi(100\text{ Hz})(1.00 \times 10^{-7}\text{ F})} = 15{,}900\ \Omega$$

Increasing the frequency by a factor of 10^6 decreases X_C by a factor of 10^6, giving

$$X_C (\text{at } 100\text{ MHz}) = 0.0159\ \Omega$$

ASSESS A capacitor with a substantial reactance at audio frequencies has virtually no reactance at FM radio frequencies.

EXAMPLE 26.7 Finding a capacitor's current

A 10 μF capacitor is connected to a 1000 Hz oscillator with a peak emf of 5.0 V. What is the peak current through the capacitor?

PREPARE The circuit diagram is as in Figure 26.15b. This is a simple one-capacitor circuit.

SOLVE The capacitive reactance at $f = 1000$ Hz is

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(1000\text{ Hz})(10 \times 10^{-6}\text{ F})} = 16\ \Omega$$

The peak voltage across the capacitor is $V_C = \mathcal{E}_0 = 5.0$ V; hence the peak current is

$$I_C = \frac{V_C}{X_C} = \frac{5.0\text{ V}}{16\ \Omega} = 0.31\text{ A}$$

ASSESS Using reactance and Equation 26.21 is just like using resistance and Ohm's law, but don't forget that it applies to only the *peak* current and voltage, not the instantaneous values. Further, reactance, unlike resistance, depends on the frequency of the signal.

STOP TO THINK 26.2 A capacitor is attached to an AC voltage source. Which change will result in a doubling of the current?

A. Halving the voltage and doubling the frequency
B. Doubling the frequency
C. Halving the frequency
D. Doubling the voltage and halving the frequency

26.6 Inductors and Inductor Circuits

FIGURE 26.18 shows a length of wire formed into a coil, making a solenoid. In Chapter 24 you learned that current in a solenoid creates a magnetic field inside the solenoid. If this current is *increasing,* as shown in Figure 26.18a, then the magnetic field—and thus the flux—inside the coil increases as well. According to Faraday's law, this changing flux causes an emf—a potential difference—to develop across the coil. The *direction* of the emf can be inferred from Lenz's law: Its direction must be such to *oppose* the increase in the flux; that is, it must oppose the increase in the current. The emf will have the opposite sign if the current through the coil is decreasing, as shown in Figure 26.18b.

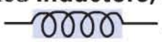
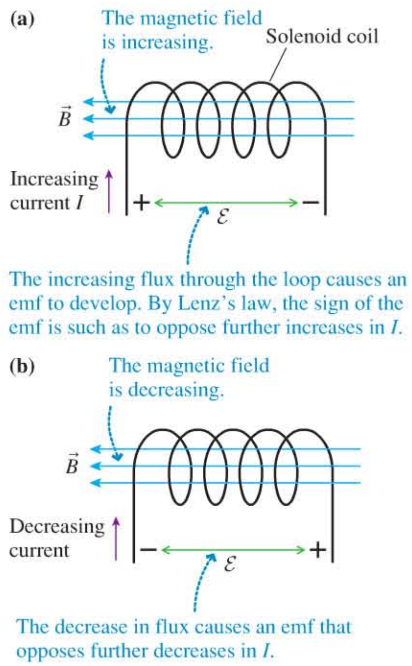
Coils of this kind, called **inductors,** are widely used in AC circuits. The circuit symbol for an inductor is . There are two primary things to remember about an inductor. First, **an inductor develops a potential difference across it if the current through it is *changing.*** Second, because the direction of this potential difference opposes the change in the current, **an inductor resists changes in the current through it.**

FIGURE 26.18 A changing current through a solenoid induces an emf across the solenoid.



Is anybody up there? Detectors are often installed beneath the pavement to sense the presence of cars waiting at intersections and on stretches of road before traffic lights. A slot is cut in the pavement. A wire is then sealed into the slot, forming an inductor consisting of a single loop. The steel in a car over the loop acts just like the iron core of an ordinary inductor, greatly increasing the inductance of the loop. This change in inductance signals that a car is present.

Inductance

By Faraday's law, the voltage developed across an inductor is proportional to the rate at which the flux through the coil changes. And, because the flux is proportional to the coil's current, the instantaneous inductor voltage v_L must be proportional to $\Delta i_L/\Delta t$, the rate at which the current through the inductor changes. Thus we can write

$$v_L = L\frac{\Delta i_L}{\Delta t} \tag{26.22}$$

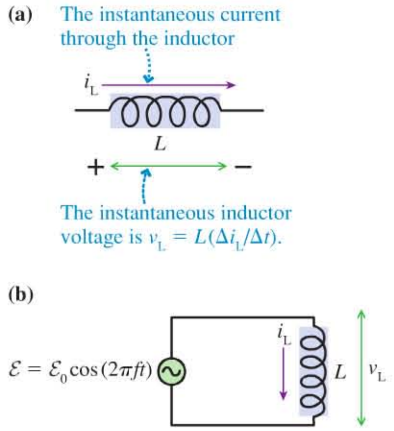
The constant of proportionality L is called the **inductance** of the inductor. The inductance is determined by the shape and size of the coil. A coil with many turns has a higher inductance than a similarly sized coil with fewer turns. Inductors often have an iron core inside their windings to increase their inductance. The magnetic field from the current magnetizes the iron core, which greatly increases the overall field through the windings. This gives a larger change in flux through the windings and hence a larger induced emf. Equation 26.22 shows that this implies a larger value of L.

From Equation 26.22 we see that inductance has units of V · s/A. It's convenient to define an SI unit of inductance called the **henry,** in honor of Joseph Henry, an early investigator of magnetism. We have

$$1 \text{ henry} = 1 \text{ H} = 1 \text{ V} \cdot \text{s/A}$$

Practical inductances are usually in the range of millihenries (mH) or microhenries (μH).

FIGURE 26.19 An AC inductor circuit.



Inductor Circuits

FIGURE 26.19a shows the instantaneous current i_L through an inductor. If the current is changing, the instantaneous inductor voltage is given by Equation 26.22.

FIGURE 26.19b, where inductance L is connected across an AC source of emf $\mathcal{E}$, is the simplest inductor circuit. The inductor is in parallel with the source, so the inductor voltage equals the emf: $v_L = \mathcal{E} = \mathcal{E}_0\cos(2\pi ft)$. We can write

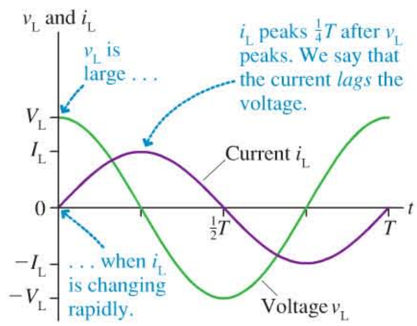
$$v_L = V_L\cos(2\pi ft) \tag{26.23}$$

where V_L is the peak or maximum voltage across the inductor. You can see that $V_L = \mathcal{E}_0$ in this single-inductor circuit.

We can find the inductor current i_L by considering again Equation 26.22, which tells us that the inductor voltage is high when the current is changing rapidly (i.e., $\Delta i_L/\Delta t$ is large) and is low when the current is changing slowly (i.e., $\Delta i_L/\Delta t$ is small). From this, we can graphically find the current, as shown in FIGURE 26.20.

Just as for a capacitor, the current and voltage are not in phase. There is again a phase difference of one-quarter cycle, but for an inductor the current peaks one-quarter period *after* the voltage peaks. **The AC current through an inductor *lags* the inductor voltage.**

FIGURE 26.20 Voltage and current graphs for an inductor in an AC circuit.



Inductive Reactance

To find the relationship between the peak values of the inductor's current and voltage, we can use Equation 26.22 and, as we did for the capacitor, the analogy with simple harmonic motion. For the oscillating capacitor voltage, with peak value $(v_C)_{max} = V_C$, the maximum value of $\Delta v_C/\Delta t$ was $(\Delta v_C/\Delta t)_{max} = 2\pi f V_C$. If an oscillating inductor current has peak value $(i_L)_{max} = I_L$, then, by exactly the same reasoning, the maximum value of $\Delta i_L/\Delta t$ is $(\Delta i_L/\Delta t)_{max} = 2\pi f I_L$. If we use this result in Equation 26.22, we see that the maximum or peak value of the inductor voltage is

$$V_L = L(2\pi f I_L) = (2\pi f L)I_L \tag{26.24}$$

We can write Equation 26.24 in a form reminiscent of Ohm's law:

$$I_L = \frac{V_L}{X_L} \quad \text{or} \quad V_L = I_L X_L \tag{26.25}$$

Peak current through or voltage across an inductor

where the **inductive reactance,** analogous to the capacitive reactance, is defined as

$$X_L = 2\pi f L \tag{26.26}$$

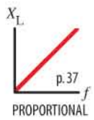


FIGURE 26.21 shows that the inductive reactance increases linearly as the frequency increases. This makes sense. Faraday's law tells us that the induced voltage across a coil increases as the rate of change of B increases, and B is directly proportional to the inductor current. For a given peak current I_L, B changes more rapidly at higher frequencies than at lower frequencies, and thus V_L is larger at higher frequencies than at lower frequencies.

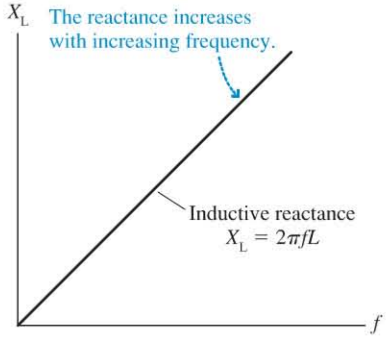


FIGURE 26.21 The inductive reactance as a function of frequency.

EXAMPLE 26.8 Finding the current and voltage of a radio's inductor

A 0.25 μH inductor is used in an FM radio circuit that oscillates at 100 MHz. The current through the inductor reaches a peak value of 2.0 mA at $t = 5.0$ ns. What is the peak inductor voltage, and when, closest to $t = 5.0$ ns, does it occur?

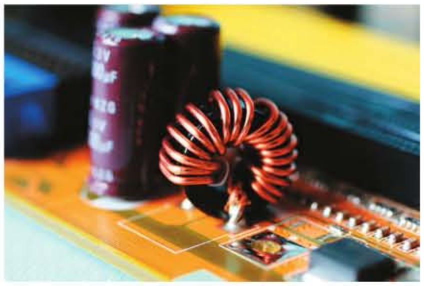
PREPARE The inductor current lags the voltage; Figure 26.20 shows that the voltage reaches its peak value one-quarter period *before* the current peaks. The circuit looks like that in Figure 26.19b.

SOLVE The inductive reactance at $f = 100\text{ MHz} = 1.0 \times 10^8$ Hz is

$$X_L = 2\pi f L = 2\pi(1.0 \times 10^8\text{ Hz})(0.25 \times 10^{-6}\text{ H}) = 160\ \Omega$$

Thus the peak voltage is $V_L = I_L X_L = (0.0020\text{ A})(160\ \Omega) = 0.32$ V. The voltage peak occurs one-quarter period before the current peaks, and we know that the current peaks at $t = 5.0$ ns. The period of a 100 MHz oscillation is 10 ns, so the voltage peaks at

$$t = 5.0\text{ ns} - \frac{10\text{ ns}}{4} = 2.5\text{ ns}$$



Clean power The digital circuits inside computers generate AC signals with frequencies of a few MHz to a few GHz. High-frequency AC currents can "leak" through the computer's power supply and propagate through your household electricity. To help prevent the transmission of such currents into or out of the computer, there will be one or more inductors on the board that connects your household electricity to the internal circuitry. At high frequencies, the inductive reactance of this inductor is very high and the high-frequency current entering or leaving is dramatically reduced.

STOP TO THINK 26.3 An inductor is attached to an AC voltage source. Which change will result in a halving of the current?

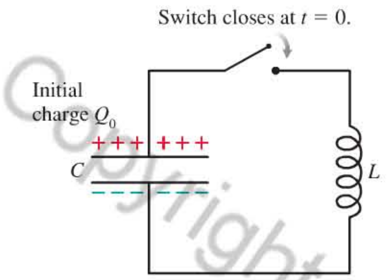
A. Halving the voltage and doubling the frequency
B. Doubling the frequency
C. Halving the frequency
D. Doubling the voltage and halving the frequency

26.7 Oscillation Circuits

All of the radio stations in your city are broadcasting all the time, but you can tune a radio to pick up one station and no other. This is done using an *oscillation circuit*, a circuit that is designed to have a particular frequency at which it "wants" to oscillate. Tuning your radio means adjusting the frequency of the oscillation circuit to equal that of the station you want to listen to. Oscillation circuits are ubiquitous in modern communications devices, but they have applications in many other areas as well.

LC Circuits

FIGURE 26.22 An *LC* circuit.

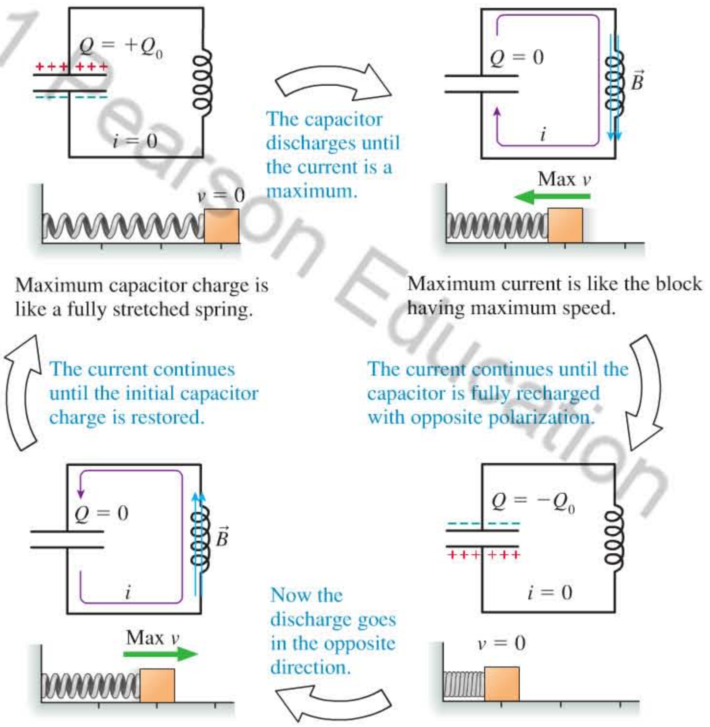


You learned in Chapter 23 that the voltage across a charged capacitor decays exponentially if the capacitor is connected to a resistor to form an *RC* circuit. Something very different occurs if the resistor is replaced with an *inductor.* Instead of decaying to zero, the capacitor voltage now undergoes sinusoidal *oscillations.*

To understand how this occurs, let's start with the capacitor and inductor shown in the ***LC* circuit** of **FIGURE 26.22**. Initially, the capacitor has charge Q_0 and there is no current in the inductor. Then, at $t = 0$, the switch is closed. How does the circuit respond?

As **FIGURE 26.23** shows, the inductor provides a conducting path for discharging the capacitor. However, the discharge current has to pass through the inductor, and, as we've seen, an inductor resists changes in current. Consequently, the current doesn't stop when the capacitor charge reaches zero.

FIGURE 26.23 The capacitor charge oscillates much like a block attached to a spring.



A block attached to a stretched spring is a useful mechanical analogy. The capacitor starts with a charge, like starting with the block pulled to the side and the spring stretched. Closing the switch to discharge the capacitor is like releasing the block. But the block doesn't stop when it reaches the origin—it keeps it going until the spring is fully compressed. Likewise, the current continues until it has recharged the capacitor with the opposite polarization. This process repeats over and over, charging the capacitor first one way, then the other. The charge and current *oscillate.*

Recall that the oscillation frequency of a mass m on a spring with spring constant k is

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The oscillation frequency thus depends only on the two basic parameters k and m of the system and not on the amplitude of the oscillation. Similarly, the frequency of an *LC* oscillator is determined solely by the values of its inductance and capacitance. We would expect larger values of L and C to cause an oscillation with a lower

A *Tesla coil* uses the driven oscillation of an *LC* circuit to produce very high voltages. Careful tuning of the circuit is necessary to produce the dramatic discharges shown.

frequency, because a larger inductance means the current changes more slowly and a larger capacitance takes longer to discharge. A detailed analysis shows that the frequency has a form reminiscent of that for a mass and spring:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{26.27}$$

Frequency of an LC oscillator

EXAMPLE 26.9 The frequency of an *LC* oscillator

An LC circuit consists of a 10 μH inductor and a 500 pF capacitor. What is the oscillator's frequency?

SOLVE From Equation 26.27 we have

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(10\times10^{-6}\ \text{H})(500\times10^{-12}\ \text{F})}} = 2.3\times10^{6}\ \text{Hz} = 2.3\ \text{MHz}$$

ASSESS The frequencies of LC oscillators are generally *much* higher than those of mechanical oscillators. Frequencies in the MHz or even GHz (10^9 Hz) range are typical.

RLC Circuits

Once the oscillations of the ideal LC circuit of Figure 26.23 are started, they will continue forever. All real circuits, however, have some resistance, either from the small resistance of the wires that make up the circuit or from actual circuit resistors. These resistors dissipate energy, causing the amplitudes of the voltages and currents to decay.

We can model this situation by adding a series resistor R to our LC circuit, as shown in FIGURE 26.24. The circuit still oscillates, but the peak values of the voltage and current decrease with time as the current through the resistor transforms the electric and magnetic energy of the circuit into thermal energy. Because the power loss is proportional to R, a larger resistance causes the oscillations to decay more rapidly, as shown in FIGURE 26.25. This behavior is completely analogous to the damped harmonic oscillator discussed in Chapter 14.

To keep the circuit oscillating, we need to add an AC source to the circuit. This makes the **driven *RLC* circuit** of FIGURE 26.26. Because the reactances of the capacitor and inductor vary with the frequency of the AC source, the current in this circuit varies with frequency as well.

Recall that the reactance of a capacitor or inductor plays the same role for the peak quantities I and V as does the resistance of a resistor. When the reactance is large, the current through the capacitor or inductor is small. Because this is a series circuit, with the same current throughout, any circuit element with a large resistance or reactance can block the current.

If the AC source frequency f is very small, the capacitor's reactance $X_C = 1/(2\pi fC)$ is extremely large. If the source frequency f becomes very large, the inductor's reactance $X_L = 2\pi fL$ becomes extremely large. This has two consequences. First, the current in the driven RLC circuit will approach zero at very low and very high frequencies. Second, there must be some intermediate frequency, where neither X_C nor X_L is too large, at which the circuit current I is a maximum. The frequency f_0 at which the current is at its maximum value is called the **resonance frequency.**

Resonance occurs at the frequency at which the capacitive reactance equals the inductive reactance. If the reactances are equal, the capacitor voltage and the inductor voltage are the same. But these two voltages are out of phase with the current, with the current *leading* the capacitor voltage and *lagging* the inductor voltage. At

FIGURE 26.24 An *RLC* circuit.

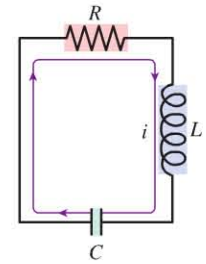


FIGURE 26.25 An *RLC* circuit exhibits damped oscillations.

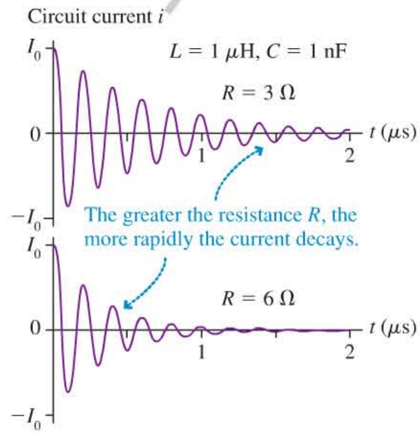
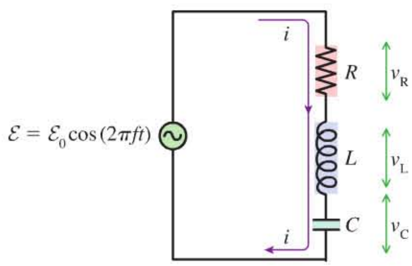
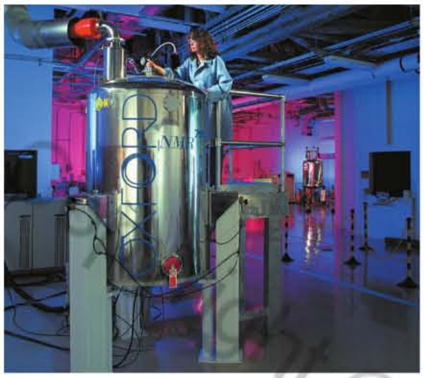


FIGURE 26.26 A driven *RLC* circuit.





Nuclear magnetic resonance, or *nmr,* is an important analytic technique in chemistry and biology. In a large magnetic field, the magnetic moments of atomic nuclei rotate at tens to hundreds of MHz. This motion generates a changing magnetic field that induces an AC emf in a coil placed around the sample. Each kind of nucleus rotates at a characteristic frequency. Adding a capacitor to the coil creates an *RLC* resonance circuit that responds strongly to only one frequency—and hence to one kind of nucleus.

resonance, the capacitor and inductor voltages have equal magnitudes but are exactly out of phase with each other. When we add all the voltages around the loop in Kirchhoff's loop law, the capacitor and inductor voltages cancel and the current is then limited only by the resistance R. Thus the condition for resonance is $X_C = X_L$, or

$$\frac{1}{2\pi f_0 C} = 2\pi f_0 L$$

which gives

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{26.28}$$

This is the same frequency at which the circuit would oscillate if it had no resistor. At this frequency maximum current is determined by the magnitude of the emf and the resistance:

$$I_{\text{max}} = \frac{\mathcal{E}_0}{R} \tag{26.29}$$

The driven *RLC* circuit is directly analogous to the driven, damped oscillator that you studied in Chapter 14. A mechanical oscillator exhibits resonance by having a large-amplitude response when the driving frequency matches the system's natural frequency. Equation 26.28 is the natural frequency of the driven *RLC* circuit, the frequency at which the current would like to oscillate. The circuit has a large current response when the oscillating emf matches this frequency.

FIGURE 26.27 A graph of the current I versus emf frequency for a series *RLC* circuit.

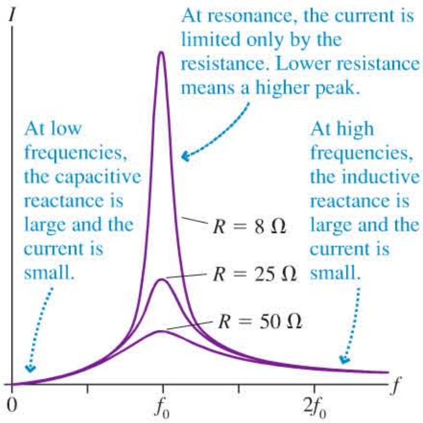


FIGURE 26.27 shows the peak current I of a driven *RLC* circuit as the emf frequency f is varied. Notice how the current increases until reaching a maximum at frequency f_0, then decreases. This is the hallmark of resonance.

As R decreases, causing the damping to decrease, the maximum current becomes larger and the curve in Figure 26.27 becomes narrower. You saw exactly the same behavior for a driven mechanical oscillator. The emf frequency must be very close to f_0 in order for a lightly damped system to respond, but the response at resonance is very large—exactly what is needed for a tuning circuit.

It is possible to derive an expression for the current graphs shown in Figure 26.27. The peak current in the *RLC* circuit is

$$I = \frac{\mathcal{E}_0}{\sqrt{R^2 + (X_L - X_C)^2}} = \frac{\mathcal{E}_0}{\sqrt{R^2 + (2\pi f L - 1/2\pi f C)^2}} \tag{26.30}$$

Peak current in an *RLC* circuit

14.2, 14.3 ActivPhysics Online

Note that the denominator is smallest, and hence the current is largest, when $X_L = X_C$; that is, at resonance. The three peak voltages, if you need them, are then found from $V_R = IR$, $V_L = IX_L$, and $V_C = IX_C$.

EXAMPLE 26.10 **Designing a radio receiver**

An AM radio antenna picks up a 1000 kHz signal with a peak voltage of 5.0 mV. The tuning circuit consists of a 60 μH inductor in series with a variable capacitor. The inductor coil has a resistance of 0.25 Ω, and the resistance of the rest of the circuit is negligible.

a. To what value should the capacitor be tuned to listen to this radio station?
b. What is the peak current through the circuit at resonance?
c. A stronger station at 1050 kHz produces a 10 mV antenna signal. What is the current at this frequency when the radio is tuned to 1000 MHz?

PREPARE The inductor's 0.25 Ω resistance can be modeled as a resistance in series with the inductance; hence we have a series *RLC* circuit. The antenna signal at $f = 1000$ kHz $= 10^6$ Hz is the emf. The circuit looks like that in Figure 26.26.

SOLVE

a. The capacitor needs to be tuned so that the resonant frequency of the circuit is $f_0 = 1000$ kHz. Because $f_0 = 1/2\pi\sqrt{LC}$, the appropriate capacitance is

$$C = \frac{1}{L(2\pi f_0)^2} = \frac{1}{(60 \times 10^{-6}\ \text{H})(2\pi \times 10^6\ \text{Hz})^2}$$
$$= 4.2 \times 10^{-10}\ \text{F} = 420\ \text{pF}$$

b. $X_L = X_C$ at resonance, so the maximum current is

$$I_{max} = \frac{\mathcal{E}_0}{R} = \frac{5.0 \times 10^{-3}\ \text{V}}{0.25\ \Omega} = 0.020\ \text{A} = 20\ \text{mA}$$

c. The 1050 kHz signal is "off resonance," so the reactances X_L and X_C are not equal: $X_L = 2\pi fL = 396\ \Omega$ and $X_C = 1/2\pi fC = 361\ \Omega$ at $f = 1050$ kHz. The peak voltage of this signal is $\mathcal{E}_0 = 10$ mV. With these values, Equation 26.30 for the peak current is

$$I = \frac{\mathcal{E}_0}{\sqrt{R^2 + (X_L - X_C)^2}} = 0.29\ \text{mA}$$

ASSESS These are realistic values for the input stage of an AM radio. You can see that the signal from the 1050 kHz station is strongly suppressed when the radio is tuned to 1000 kHz. The resonant circuit has a large response to the selected station, but not nearby stations.

STOP TO THINK 26.4 A driven *RLC* circuit has $V_C = 5.0$ V, $V_R = 7.0$ V, and $V_L = 9.0$ V. Is the frequency higher than, lower than, or equal to the resonance frequency?

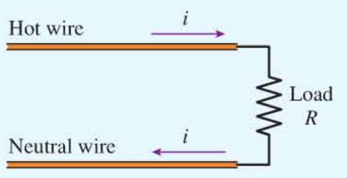
INTEGRATED EXAMPLE 26.11 The ground fault interrupter

As we've seen, a GFI disconnects a household circuit when the currents in the hot and neutral wires are unequal. Let's look inside a GFI outlet to see how this is done.

When you plug something in, the load completes the circuit between the hot and neutral wires. The current varies in the AC circuit thus produced, but at any instant the currents in the hot and neutral wires are equal and opposite, as FIGURE 26.28 shows.

If someone accidentally touches a hot wire—a potentially dangerous situation—some of the current in the hot wire is diverted to a different path. The currents in the hot and neutral wires are no longer equal. This difference is sensed by the GFI, and the outlet is switched off.

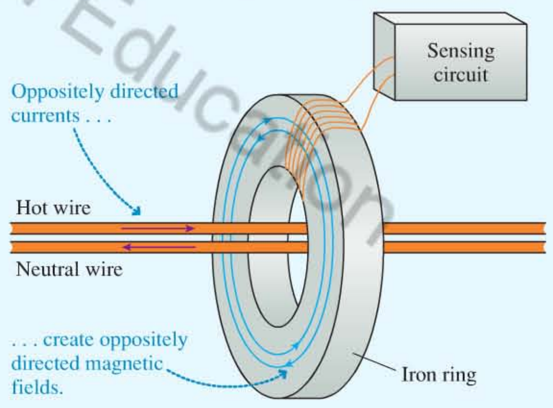
FIGURE 26.28 Currents in the wires in an electric outlet.



This determination is made inside the GFI outlet as shown in FIGURE 26.29. The hot and neutral wires thread through an iron ring. A coil of fine wire wraps around the ring; this coil is connected to a circuit that detects any current in the coil.

If the currents in the hot and neutral wires are equal and opposite, the magnetic fields of the two wires are equal and opposite. There is no net magnetic field in the iron ring, and thus no flux through the sensing coil. But if the two currents aren't equal, there is a net field. The current is AC, so this field isn't constant; it is changing. This field magnetizes the iron ring, increasing the overall field strength and producing a significant (and changing) flux through the sensing coil. According to Faraday's law, this changing flux induces a current in the coil.

FIGURE 26.29 The working elements of a GFI outlet.



The sensing circuit detects this current and opens a small circuit breaker to turn the outlet off within a few milliseconds, in time to prevent any injury.

a. A GFI will break the circuit if the difference in current between the hot and neutral wires is 5.0 mA. Suppose that, at some instant, there is an excess current of 5.0 mA to the right in the hot wire of Figure 26.29. What are the direction and the magnitude of the magnetic field due to the wire in the iron ring? The ring has an average diameter of 0.80 cm.

b. Consider a worst-case scenario: A person immersed in the bathtub reaches out of the tub and accidentally touches a hot wire with a wet, soapy hand that has minimal skin resistance. What would be the peak current through the person's body? Would this be dangerous? Would a GFI disconnect the circuit?

c. If you connect a capacitor to an outlet, the current and voltage will be out of phase, as we've seen. Would this trigger a GFI?

Continued

PREPARE Part a is about the magnetic fields of the wires. The currents in the hot and neutral wires create a field around the wires, as we saw in Chapter 24. If there is an excess current in the hot wire to the right, the right-hand rule tells us that the field will be clockwise through the iron ring in the view of Figure 26.29. We can use Equation 24.1 to find the magnitude of the magnetic field. Part b is an electrical safety question; we will need to find the resistance of the current path through the body to find the current.

SOLVE a. The iron ring has an average diameter of 0.80 cm, so we need to find the field at a distance of 0.40 cm from the wire. Equal currents produce no net field, so we need only consider the field due to the excess current in the hot wire. We learned in Chapter 24 that the field of a long, straight, current-carrying wire is $B = \mu_0 I/2\pi r$. Thus

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \mathrm{T \cdot m/A})(5.0 \times 10^{-3}\ \mathrm{A})}{2\pi(0.0040\ \mathrm{m})}$$

$$= 2.5 \times 10^{-7}\ \mathrm{T} = 0.25\ \mu T$$

We noted above that the direction of this field is clockwise.

b. The person in the tub is sitting in conducting water that is well grounded. If this person touches a hot wire, there is a current path from the hot wire to ground, as **FIGURE 26.30a** shows. Resistance values for elements of the body are as noted in Figure 26.12. Because of the negligible skin resistance of a wet, soapy hand, the equivalent resistance of the body is the sum of the resistance of the arm and the torso: $R_{\mathrm{eq}} = 340\ \Omega$.

Given that the neutral wire of the electricity supply is also grounded, there is a complete circuit through the person, as shown in **FIGURE 26.30b**. The peak current in this circuit, occurring at the peak of the sinusoidal household AC voltage ($\mathcal{E}_0 = 170\,\mathrm{V}$), is

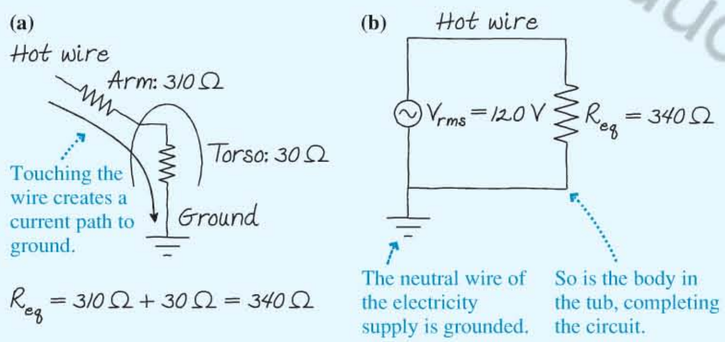
$$I_{\mathrm{R}} = \frac{\mathcal{E}_0}{R_{\mathrm{eq}}} = \frac{170\ \mathrm{V}}{340\ \Omega} = 0.50\ \mathrm{A}$$

Table 26.1 shows that this is a very dangerous level of current, likely to be fatal. Fortunately, it's also well above the threshold for detection by the GFI, which will quickly disconnect the circuit.

c. A difference in phase between voltage and current won't affect the GFI. The GFI detects a difference in current between two wires. As we've seen, the currents into and out of a capacitor are always equal, with no difference between them, so the presence of a capacitor in the circuit will not affect the operation of the GFI.

ASSESS The worst-case scenario is one that you could imagine happening if a person in a bathtub touches a faulty radio or picks up a faulty hair dryer. It's a situation you would expect to be dangerous, in which we'd expect a GFI to come into play.

FIGURE 26.30 The resistance of the path through the body and the resulting circuit.



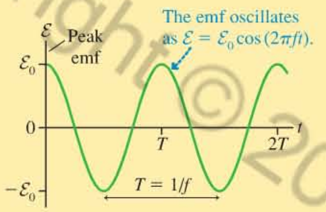
SUMMARY

The goal of Chapter 26 has been to understand and apply basic principles of AC electricity, electricity transmission, and household electricity.

IMPORTANT CONCEPTS

AC circuits

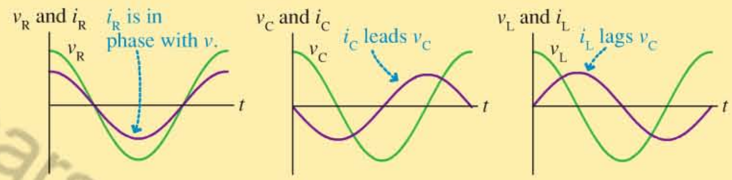
AC circuits are driven by an emf that oscillates with frequency f.



- Peak values of voltages and currents are denoted by capital letters: I, V.
- Instantaneous values of voltages and currents are denoted by lowercase letters: i, v.

Circuit elements used in AC circuits

	Resistor	Capacitor	Inductor
Symbol			
Reactance	Resistance R is constant	$X_C = 1/(2\pi f C)$	$X_L = 2\pi f L$
I and V	$V_R = I_R R$	$V_C = I_C X_C$	$V_L = I_L X_L$
Graph			



Power in AC resistor circuits

The average power dissipated by a resistor is

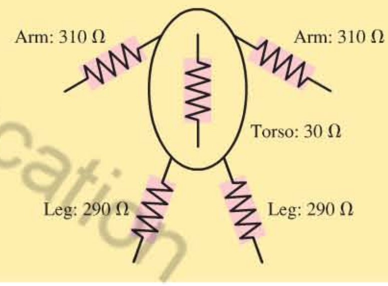
$$P_R = (I_{rms})^2 R = \frac{(V_{rms})^2}{R} = I_{rms} V_{rms}$$

where $I_{rms} = I_R/\sqrt{2}$ and $V_{rms} = V_R/\sqrt{2}$ are the root-mean-square (rms) voltage and current.

Electrical safety and biological effects

Currents passing through the body can produce dangerous effects. Currents larger than 15 mA (AC) and 60 mA (DC) are potentially fatal.

The body can be modeled as a network of resistors. If the body forms a circuit between two different voltages, the current is given by Ohm's law: $I = \Delta V/R$.



APPLICATIONS

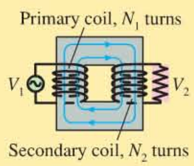
Transformers

Transformers are used to increase or decrease an AC voltage. The rms voltage at the secondary is related to the rms voltage at the primary by

$$(V_2)_{rms} = \frac{N_2}{N_1}(V_1)_{rms}$$

and the currents are related by

$$(I_2)_{rms} = \frac{N_1}{N_2}(I_1)_{rms}$$

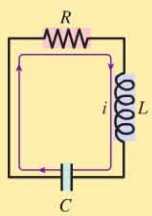


LC and *RLC* circuits

In an LC circuit, the current and voltages oscillate with frequency

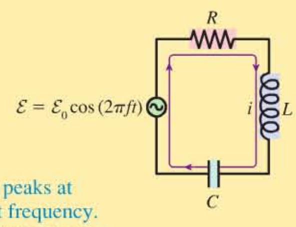
$$f = \frac{1}{2\pi\sqrt{LC}}$$

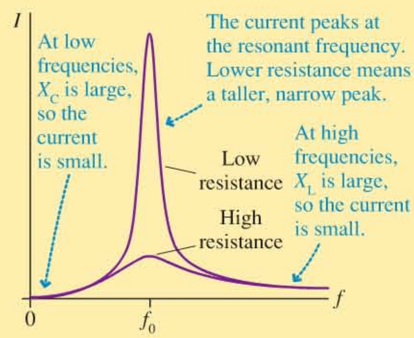
In the RLC circuit, the oscillations decay as energy is dissipated in the resistor.



The driven *RLC* circuit

If an AC source of amplitude $\mathcal{E}_0$ is placed in an RLC circuit, then the voltages and currents oscillate continuously.





- The **resonance frequency** is $f_0 = \dfrac{1}{2\pi\sqrt{LC}}$.
- The maximum value of the current is $I_{max} = \mathcal{E}_0/R$.
- The peak current at any frequency f is given by

$$I = \frac{\mathcal{E}_0}{\sqrt{R^2 + (X_L - X_C)^2}}$$

VIEW ALL SOLUTIONS

QUESTIONS

Conceptual Questions

1. Identical resistors are connected to separate 12 V AC sources. One source operates at 60 Hz, the other at 120 Hz. In which circuit, if either, does the resistor dissipate the greater average power?
2. Consider the three circuits in Figure Q26.2. Rank in order, from largest to smallest, the average total powers P_1 to P_3 dissipated by all the resistors in each circuit. Explain.

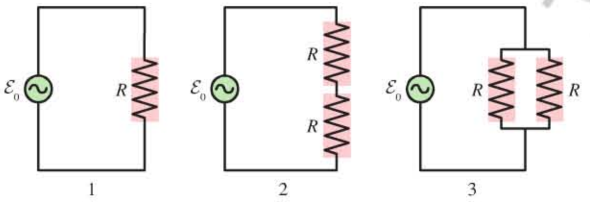


FIGURE Q26.2

3. Lightbulbs in AC circuits "flicker" in intensity, though the flickering is too fast for your eyes to sense it. If a light bulb is connected to a 120 V/60 Hz power supply, how many times a second does the bulb reach peak brightness?
4. A household wall outlet can provide no more than 15 A, but you can use this outlet to power an electric soldering iron that drives 150 A through the metal tip. How is this possible?
5. A 12 V DC power supply is connected to the primary coil of a transformer. The primary coil has 100 turns and the secondary coil has 200. What is the rms voltage across the secondary?
6. Figure Q26.6 shows three wires wrapped around an iron core. The number of turns and the directions of the windings in the figure should be carefully noted. At one particular instant, $V_A - V_B = 20$ V. At that same instant, what is $V_C - V_D$?

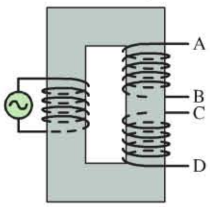


FIGURE Q26.6

7. BIO Women usually have higher resistance of their arms and legs than men. Why might you expect to see this variation in resistance?
8. BIO A circuit breaker won't keep you from getting a shock; a GFI will. Explain why this is so.
9. Your cell phone charger plugs into an AC electric outlet. A typical charger has a two-prong plug. Either prong can go in the hot side of the outlet; that is, you can reverse the plug and the charger still works. Your cell phone runs on DC current from a battery. If you reverse the battery, the phone won't operate. Explain why you can reverse the polarity of an AC source like an electric outlet, but not a DC source like a battery.
10. BIO New homes are required to have GFI-protected outlets in bathrooms, kitchens, and any outdoor locations. Why is GFI protection required in these locations but not, say, in bedrooms?
11. Your computer has a built-in "surge protector." A surge is a sudden increase in voltage on the power line. This causes a rapid "current spike" that can destroy sensitive electronic components. After the AC electricity is converted to DC in your computer's power supply, the current going to the computer processor must pass through a coil of wire wrapped around an iron core. Explain how this coil works as a surge suppressor.
12. The peak current through a resistor is 2.0 A. What is the peak current if
    a. The resistance R is doubled?
    b. The peak emf $\mathcal{E}_0$ is doubled?
    c. The frequency f is doubled?
13. The average power dissipated by a resistor is 4.0 W. What is the average power if
    a. The resistance R is doubled?
    b. The peak emf $\mathcal{E}_0$ is doubled?
    c. Both are doubled simultaneously?
14. The peak current through a capacitor is 2.0 A. What is the peak current if
    a. The peak emf $\mathcal{E}_0$ is doubled?
    b. The capacitance C is doubled?
    c. The frequency f is doubled?
15. Consider the four circuits in Figure Q26.15. Rank in order, from largest to smallest, the capacitive reactances $(X_C)_1$ to $(X_C)_4$. Explain.

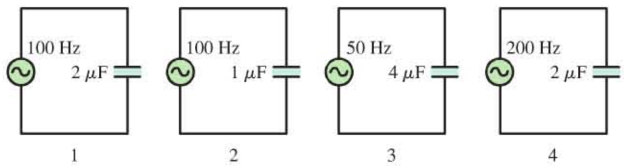


FIGURE Q26.15

16. An inductor is plugged into a 120 V/60 Hz wall outlet in the U.S. Would the peak current be larger, smaller, or unchanged if this inductor were plugged into a wall outlet in a country where the voltage is 120 V at 50 Hz? Explain.
17. Figure Q26.17 shows two inductors and the potential difference across them at time $t = 0$ s.
    a. Can you tell which of these inductors has the larger current flowing through it at $t = 0$ s? If so, which one? If not, why not?
    b. Can you tell through which inductor the current is changing more rapidly at $t = 0$ s? If so, which one? If not, why not?

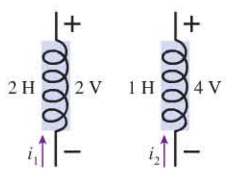


FIGURE Q26.17

18. The peak current passing through an inductor is 2.0 A. What is the peak current if:
    a. The peak emf $\mathcal{E}_0$ is doubled?
    b. The inductance L is doubled?
    c. The frequency f is doubled?
19. Consider the four circuits in Figure Q26.19. Rank in order, from largest to smallest, the inductive reactances $(X_L)_1$ to $(X_L)_4$. Explain.

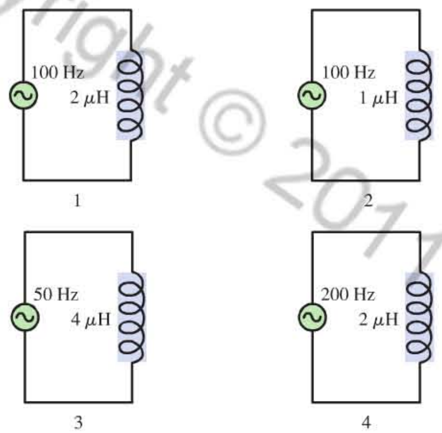


FIGURE Q26.19

20. The tuning circuit in a radio uses an *RLC* circuit. Will adjusting the resistance have any effect on the resonance frequency?
21. The resonance frequency of a driven *RLC* circuit is 1000 Hz. What is the resonance frequency if
    a. The resistance R is doubled?
    b. The inductance L is doubled?
    c. The capacitance C is doubled?
    d. The peak emf $\mathcal{E}_0$ is doubled?
    e. The emf frequency f is doubled?
22. Consider the four circuits in Figure Q26.22. They all have the same resonance frequency f_0 and are driven by the same emf. Rank in order, from largest to smallest, the maximum currents $(I_{max})_1$ to $(I_{max})_4$. Explain.

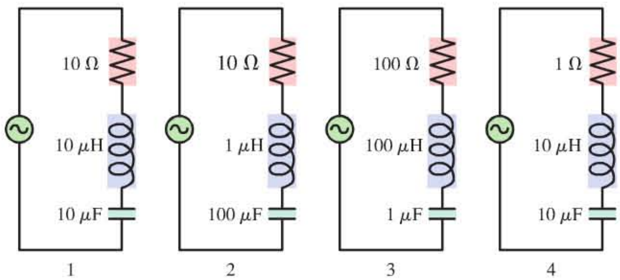


FIGURE Q26.22

Multiple-Choice Questions

23. A transformer has 1000 turns in the primary coil and 100 turns in the secondary coil. If the primary coil is connected to a 120 V outlet and draws 0.050 A, what are the voltage and current of the secondary coil?
    A. 1200 V, 0.0050 A
    B. 1200 V, 0.50 A
    C. 12 V, 0.0050 A
    D. 12 V, 0.50 A
24. An inductor is connected to an AC generator. As the generator's frequency is increased, the current in the inductor
    A. Increases.
    B. Decreases.
    C. Does not change.
25. A capacitor is connected to an AC generator. As the generator's frequency is increased, the current in the capacitor
    A. Increases.
    B. Decreases.
    C. Does not change.
26. An AC source is connected to a series combination of a lightbulb and a variable inductor. If the inductance is increased, the bulb's brightness
    A. Increases.
    B. Decreases.
    C. Does not change.
27. An AC source is connected to a series combination of a lightbulb and a variable capacitor. If the capacitance is increased, the bulb's brightness
    A. Increases.
    B. Decreases.
    C. Does not change.
28. The circuit shown in Figure Q26.28 has a resonance frequency of 15 kHz. What is the value of L?
    A. 1.6 μH
    B. 2.4 μH
    C. 5.2 μH
    D. 18 μH
    E. 59 μH

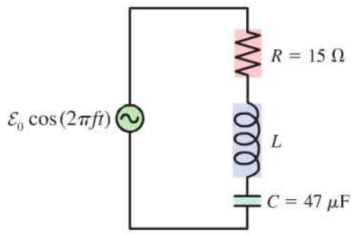


FIGURE Q26.28

PROBLEMS

Section 26.1 Alternating Current

1. | A 200 Ω resistor is connected to an AC source with $\mathcal{E}_0 = 10$ V. What is the peak current through the resistor if the emf frequency is (a) 100 Hz? (b) 100 kHz?

2. | Figure P26.2 shows voltage and current graphs for a resistor.
   a. What is the value of the resistance R?
   b. What is the emf frequency f?

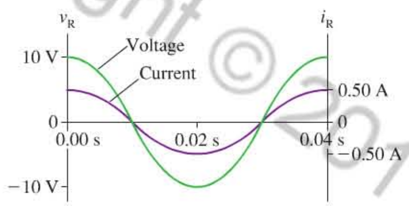


FIGURE P26.2

3. || A resistor dissipates 2.00 W when the rms voltage of the emf is 10.0 V. At what rms voltage will the resistor dissipate 10.0 W?

4. | The heating element of a hair dryer dissipates 1500 W when connected to a 120 V/60 Hz power line. What is its resistance?

5. || A toaster oven is rated at 1600 W for operation at 120 V/60 Hz.
   a. What is the resistance of the oven heater element?
   b. What is the peak current through it?
   c. What is the peak power dissipated by the oven?

6. || A 100 Ω resistor is connected to a 120 V/60 Hz power line. What is its average power loss?

7. || A generator produces 40 MW of power and sends it to town at an rms voltage of 75 kV. What is the rms current in the transmission lines?

8. | Soles of boots that are designed to protect workers from electric shock are rated to pass a maximum rms current of 1.0 mA when connected across an 18,000 V AC source. What is the minimum allowed resistance of the sole? BIO

Section 26.2 AC Electricity and Transformers

9. | The primary coil of a transformer is connected to a 120 V/60 Hz wall outlet. The secondary coil is connected to a lamp that dissipates 60 W. What is the rms current in the primary coil?

10. || A soldering iron uses an electric current in a wire to heat the tip. A transformer with 100 turns on the secondary coil provides 50 W at an rms voltage of 24 V.
    a. What is the resistance of the wire in the iron?
    b. How many turns are in the primary coil?
    c. What is the current in the primary coil?

11. || A power pack charging a cell phone battery has an output of 0.40 A at 5.2 V (both rms). What is the rms current at the 120 V/60 Hz wall outlet where the power pack is plugged in?

12. || A neon sign transformer has a 450 W AC output with an rms voltage of 15 kV when connected to a normal household outlet. There are 500 turns of wire in the primary coil.
    a. How many turns of wire does the secondary coil have?
    b. When the transformer is running at full power, what is the current in the secondary coil? The current in the primary coil?

13. || The "power cube" transformer for a portable CD player has an output of 4.5 V and 600 mA (both rms) when plugged into a 120 V/60 Hz outlet.
    a. If the primary coil has 400 turns of wire, how many turns are on the secondary coil?
    b. What is the peak current in the primary coil?

14. | A science hobbyist has purchased a surplus power-pole transformer that converts 7.2 kV from neighborhood distribution lines into 120 V for homes. He connects the transformer "backward," plugging the secondary coil into a 120 V outlet. What rms voltage is induced at the primary?

Section 26.3 Household Electricity

15. || A typical American family uses 1000 kWh of electricity a month.
    a. What is the average rms current in the 120 V power line to the house?
    b. On average, what is the resistance of a household?

16. || The wiring in the wall of your house to and from an outlet has a total resistance of typically 0.10 Ω. Suppose a device plugged into a 120 V outlet draws 10.0 A of current. INT
    a. What is the voltage drop along the wire?
    b. How much power is dissipated in the wire?
    c. What is the voltage drop across the device?
    d. At what rate does the device use electric energy?

17. | The following appliances are connected to a single 120 V, 15 A circuit in a kitchen: a 330 W blender, a 1000 W coffeepot, a 150 W coffee grinder, and a 750 W microwave oven. If these are all turned on at the same time, will they trip the circuit breaker? INT

18. || A 60 W (120 V) night light is turned on for an average 12 hr a day year round. What is the annual cost of electricity at a billing rate of $0.10/kWh?

19. || Suppose you leave a 110 W television and two 100 W lightbulbs on in your house to scare off burglars while you go out dancing. If the cost of electric energy in your town is $0.12/kWh and you stay out for 4.0 hr, how much does this robbery-prevention measure cost?

20. ||| The manufacturer of an electric table saw claims that it has a 3.0 hp motor. It is designed to be used on a normal 120 V outlet with a 15 A circuit breaker. Is this claim reasonable? Explain. INT

Section 26.4 Biological Effects and Electrical Safety

21. || If you touch the terminal of a battery, the small area of contact means that the skin resistance will be relatively large; 50 kΩ is a reasonable value. What current will pass through your body if you touch the two terminals of a 9.0 V battery with your two hands? Will you feel it? Will it be dangerous? BIO

22. II A person standing barefoot on the ground 20 m from the point of a lightning strike experiences an instantaneous potential difference of 300 V between his feet. If we assume a skin resistance of 1.0 kΩ, how much current goes up one leg and back down the other? BIO

23. II Electrodes used to make electrical measurements of the body (such as those used when recording an electrocardiogram) use a conductive paste to reduce the skin resistance to very low values. If you have such an electrode on one wrist and one ankle, what are the lowest AC and DC voltages that will give you a perceptible shock? A potentially fatal shock? BIO

24. II A fisherman has netted a torpedo ray. As he picks it up, this electric fish creates a short-duration 50 V potential difference between his hands. His hands are wet with salt water, and so his skin resistance is a very low 100 Ω. What current passes through his body? Will he feel this DC pulse? BIO

Problems 25 and 26 concern a high-voltage transmission line. Such lines are made of bare wire; they are not insulated. Assume that the wire is 100 km long, has a resistance of 7.0 Ω, and carries 200 A.

25. III A bird is perched on the wire with its feet 2.0 cm apart. What is the potential difference between its feet? INT BIO

26. III Would it be possible for a person to safely hang from this wire? Assume that the hands are 15 cm apart, and assume a skin resistance of 2200 Ω. BIO INT

Section 26.5 Capacitor Circuits

27. II A 0.30 μF capacitor is connected across an AC generator that produces a peak voltage of 10.0 V. What is the peak current through the capacitor if the emf frequency is (a) 100 Hz? (b) 100 kHz?

28. II A 20 μF capacitor is connected across an AC generator that produces a peak voltage of 6.0 V. The peak current is 0.20 A. What is the oscillation frequency in Hz?

29. I The peak current through a capacitor is 10.0 mA. What is the current if
   a. The emf frequency is doubled?
   b. The emf peak voltage is doubled (at the original frequency)?
   c. The frequency is halved and, at the same time, the emf is doubled?

30. II A 20 nF capacitor is connected across an AC generator that produces a peak voltage of 5.0 V.
   a. At what frequency f is the peak current 50 mA?
   b. What is the instantaneous value of the emf at the instant when $i_C = I_C$?

31. III A capacitor is connected to a 15 kHz oscillator that produces an rms voltage of 6.0 V. The peak current is 65 mA. What is the value of the capacitance C?

32. I The peak current through a capacitor is 8.0 mA when connected to an AC source with a peak voltage of 1.0 V. What is the capacitive reactance of the capacitor?

Section 26.6 Inductors and Inductor Circuits

33. III What is the potential difference across a 10 mH inductor if the current through the inductor drops from 150 mA to 50 mA in 10 μs?

34. II A 20 mH inductor is connected across an AC generator that produces a peak voltage of 10.0 V. What is the peak current through the inductor if the emf frequency is (a) 100 Hz? (b) 100 kHz?

35. I The peak current through an inductor is 10.0 mA. What is the current if
   a. The emf frequency is doubled?
   b. The emf peak voltage is doubled (at the original frequency)?
   c. The frequency is halved and, at the same time, the emf is doubled?

36. I A 500 μH inductor is connected across an AC generator that produces a peak voltage of 5.0 V.
   a. At what frequency f is the peak current 50 mA?
   b. What is the instantaneous value of the emf at the instant when $i_L = I_L$?

37. III An inductor is connected to a 15 kHz oscillator that produces an rms voltage of 6.0 V. The peak current is 65 mA. What is the value of the inductance L?

38. I The peak current through an inductor is 12.5 mA when connected to an AC source with a peak voltage of 1.0 V. What is the inductive reactance of the inductor?

39. I The superconducting magnet in a magnetic resonance imaging system consists of a solenoid with 5.6 H of inductance. The solenoid is energized by connecting it to a 1.2 V DC power supply. Starting from zero, how long does it take for the solenoid to reach its operating current of 100 A? BIO

Section 26.7 Oscillation Circuits

40. III In a nuclear magnetic resonance spectrometer, a 15 mH coil is designed to detect an emf oscillating at 400 MHz. The coil is part of an *RLC* circuit. What value of the capacitance C should be used so that the coil circuit resonates at 400 MHz? BIO

41. II A 2.0 mH inductor is connected in parallel with a variable capacitor. The capacitor can be varied from 100 pF to 200 pF. What is the range of oscillation frequencies for this circuit?

42. II An FM radio station broadcasts at a frequency of 100 MHz. What inductance should be paired with a 10 pF capacitor to build a receiver circuit for this station?

43. II The inductor in the *RLC* tuning circuit of an AM radio has a value of 350 mH. What should be the value of the variable capacitor in the circuit to tune the radio to 740 kHz?

44. II At what frequency f do a 1.0 μF capacitor and a 1.0 μH inductor have the same reactance? What is the value of the reactance at this frequency?

45. II Two *RLC* circuits have identical capacitors but different inductors. Circuit 1 has a resonance frequency f_0 while circuit 2 has a resonance at $2f_0$. What is the ratio L_2/L_1 of the inductance in circuit 2 to the inductance in circuit 1?

46. II What capacitor in series with a 100 Ω resistor and a 20 mH inductor will give a resonance frequency of 1000 Hz?

47. II What inductor in series with a 100 Ω resistor and a 2.5 μF capacitor will give a resonance frequency of 1000 Hz?

48. II A series *RLC* circuit has a 200 kHz resonance frequency. What is the resonance frequency if
   a. The resistor value is doubled?
   b. The capacitor value is doubled?

49. | A series RLC circuit has a 200 kHz resonance frequency. What is the resonance frequency if
   a. The resistor value is doubled?
   b. The capacitor value is doubled and, at the same time, the inductor value is halved?

50. ||| An RLC circuit with a 10 μF capacitor is connected to a variable-frequency power supply with an rms output voltage of 6.0 V. The current in the circuit as a function of the driving frequency appears as in Figure P26.50. What are the values of the resistor and the inductor?

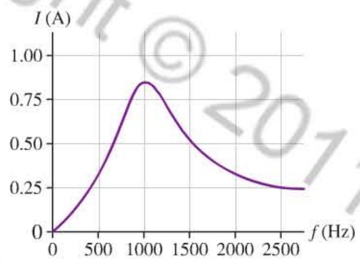


FIGURE P26.50

51. |||| A series RLC circuit consists of a 280 Ω resistor, a 25 μH inductor, and a 18 μF capacitor. What is the rms current if the emf is supplied by a standard 120 V/60 Hz wall outlet?

General Problems

52. ||| A step-down transformer converts 120 V to 24 V, which is connected to a load of resistance 8.0 Ω. What is the resistance "seen" by the power supply connected to the primary coil of the transformer?
   Hint: Resistance is defined as the ratio of two circuit quantities.

53. ||| A 15-km-long, 230 kV aluminum transmission line delivers
INT 34 MW to a city. If we assume a solid cylindrical cable, what minimum diameter is needed if the voltage decrease along this run is to be no more than 1.0% of the transmission voltage? The resistivity of aluminum is $2.7 \times 10^{-8}\ \Omega \cdot \text{m}$.

54. ||||| The outer membranes of cells are quite irregular at the sub-
BIO micron level, so the surface area of an apparently spherical cell differs from the value one would calculate from geometry. To determine the actual surface area of a cell membrane, electrophysiologists use intracellular electrodes to measure the membrane's capacitive reactance. They take advantage of the fact that the capacitance per unit area of all biological membranes is about 1.0 $\mu\text{F/cm}^2$.
   a. What is the surface area of a 20-μm-diameter sphere? Give your answer in square centimeters.
   b. The capacitive reactance of the outer membrane of a cell is measured to be $6.4 \times 10^6\ \Omega$ at 1.0 kHz. What is the surface area of the membrane, in cm^2? By what factor is the area greater than your answer to part a?

   An important biological process is the release of neurotransmitters that are involved in chemical communication between nerve cells and muscles. This release occurs when intracellular vesicles containing the neurotransmitter chemical fuse with the outer cell membrane and release their contents. The vesicle's membrane becomes part of the cell's outer membrane, increasing the latter's area. As a result, the fusion of vesicles with the outer membrane can be detected by monitoring the outer membrane's capacitive reactance. Indeed, the fusion of a single vesicle can be resolved.
   c. What is the percentage increase in the capacitive reactance of the cell considered in part b when a single vesicle's membrane, a smooth sphere 0.10 μm in diameter, fuses with the outer membrane of the cell?

55. || The voltage across a 60 μF capacitor is described by the equation $v_C = (18\text{ V})\cos(200t)$, where t is in seconds.
   a. What is the voltage across the capacitor at $t = 0.010$ s?
   b. What is the capacitive reactance?
   c. What is the peak current?

56. || The voltage across a 75 μH inductor is described by the equation $v_L = (25\text{ V})\cos(60t)$, where t is in seconds.
   a. What is the voltage across the inductor at $t = 0.10$ s?
   b. What is the inductive reactance?
   c. What is the peak current?

57. || An LC circuit is built with a 20 mH inductor and an 8.0 μF capacitor. The current has its maximum value of 0.50 A at $t = 0$ s. How long does it take until the capacitor is fully charged?

58. ||| An electronics hobbyist is building a radio set to receive the AM band, with frequencies from 520 to 1700 kHz. What range variable capacitor will she need to go with a 230 μH inductor?

59. || For the circuit of Figure P26.59,
   a. What is the resonance frequency?
   b. At resonance, what is the peak current through the circuit?

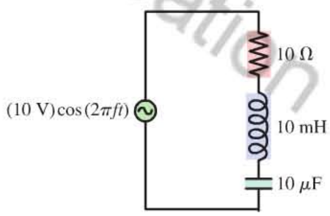


FIGURE P26.59

60. | For the circuit of Figure P26.60,
   a. What is the resonance frequency?
   b. At resonance, what is the peak current through the circuit?

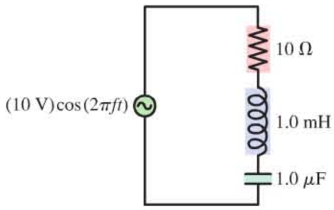


FIGURE P26.60

61. || An RLC circuit consists of a 48 Ω resistor, a 200 μF capacitor, and an inductor. The current is 2.5 A rms when the circuit is connected to a 120 V/60 Hz outlet.
   a. What is the inductance?
   b. What would be the current if this circuit were used in France, where the outlets are 220 V/50 Hz?

Passage Problems

Halogen Bulbs

Halogen bulbs have some differences from standard incandescent lightbulbs. They are generally smaller, the filament runs at a higher temperature, and they have a quartz (rather than glass) envelope. They may also operate at lower voltage. Consider a 12 V, 50 W halogen bulb for use in a desk lamp. The lamp plugs into a 120 V/60 Hz outlet, and it has a transformer in its base.

62. | The 12 V rating of the bulb refers to the rms voltage. What is the peak voltage across the bulb?
    A. 8.5 V
    B. 12 V
    C. 17 V
    D. 24 V

63. | Suppose the transformer in the base of the lamp has 500 turns of wire on its primary coil. How many turns are on the secondary coil?
    A. 50
    B. 160
    C. 500
    D. 5000

64. | How much current is drawn by the lamp at the outlet? That is, what is the rms current in the primary?
    A. 0.42 A
    B. 1.3 A
    C. 4.2 A
    D. 13 A

65. | What will be the voltage across the bulb if the lamp's power cord is accidentally plugged into a 240 V/60 Hz outlet?
    A. 12 V
    B. 24 V
    C. 36 V
    D. 48 V

STOP TO THINK ANSWERS

Stop to Think 26.1: B. The power in the AC circuit is proportional to the square of the rms current, or to $(I_{rms})^2 = (I_R/\sqrt{2})^2 = \frac{1}{2}I_R^2 = \frac{1}{2}(1\text{ A})^2$. The power in the DC circuit is proportional to the square of the DC current, or to $I_R^2 = (1\text{ A})^2$. Thus the power in the DC circuit is twice that in the AC circuit, so bulb B is brighter.

Stop to Think 26.2: B. The current is $I_C = V_C/X_C = 2\pi f C V_C$. Thus I_C is proportional to both f and V_C. Doubling the frequency while keeping V_C constant will double the current.

Stop to Think 26.3: B. The current is $I_L = V_L/X_L = V_L/2\pi f L$. Thus I_L is *inversely* proportional to f. Doubling the frequency while keeping V_L constant will halve the current.

Stop to Think 26.4: Higher than. $V_L > V_C$ tells us that $X_L > X_C$. This is the condition above resonance, where X_L is increasing with f while X_C is decreasing.

PART VI SUMMARY

Electricity and Magnetism

Mass and charge are the two most fundamental properties of matter. The first four parts of this text were about properties and interactions of masses. Part VI has been a study of charge—what charge is and how charges interact.

Electric and magnetic fields were introduced to enable us to understand the long-range forces of electricity and magnetism. One charge—the source charge—alters the space around it by creating an electric field and, if the charge is moving, a magnetic field. Other charges experience forces exerted *by the fields*. Electric and magnetic fields are the agents by which charges interact.

In addition to the electric field, we often describe electric interactions in terms of the electric potential. This is a particularly fruitful concept for dealing with electric circuits in which charges flow through wires, resistors, etc.

Electric and magnetic fields are *real* and can exist independently of charges. The clearest evidence for their independent existence is electromagnetic waves—the quintessential electromagnetic phenomenon. All electromagnetic waves, including light, are similar in structure, but they span a wide range of wavelengths and frequencies. In Part VI, we got our first hints that electromagnetic waves might have a particle-like nature, a concept we will explore further in Part VII.

Part VI has introduced many new phenomena, concepts, and laws. The knowledge structure below draws together the major ideas. These ideas build on what we've learned in the first five parts of this text. All the pieces are now in place to support the development of the ideas of modern physics in Part VII.

KNOWLEDGE STRUCTURE VI Electricity and Magnetism

BASIC GOALS How do charged particles interact? How do electric circuits work?
What are the properties and characteristics of electric and magnetic fields?

GENERAL PRINCIPLES	*Forces between charges:* **Coulomb's law**	$F_{1\text{ on }2} = F_{2\text{ on }1} = \dfrac{K\lvert q_1\rvert\lvert q_2\rvert}{r^2}$	The force is along the line connecting the charges. For like charges, the force is repulsive; for opposite charges, attractive.
	Electric force on a charge:	$\vec{F} = q\vec{E}$	The force is in the direction of the field for a positive charge; opposite the field for a negative charge.
	Magnetic force on a moving charge:	$F = \lvert q\rvert vB\sin\alpha$	The force is perpendicular to the velocity and the field, with direction as specified by the right-hand rule for forces.
	Induced emf: **Faraday's law**	$\mathcal{E} = \left\lvert\dfrac{\Delta\Phi}{\Delta t}\right\rvert$	The induced current $I = \mathcal{E}/R$ is such that the induced magnetic field opposes the *change* in the magnetic flux. This is **Lenz's law**.

Electric and magnetic fields

Charges and changing magnetic fields create electric fields.

- Electric fields exert forces on charges and torques on dipoles.
- The electric field is perpendicular to equipotential surfaces and points in the direction of decreasing potential.
- The electric field causes charges to move in conductors but not insulators.

Currents and permanent magnets create magnetic fields.

- Magnetic fields exert forces on currents (and moving charged particles) and torques on magnetic dipoles.
- A compass needle or other magnetic dipole will line up with a magnetic field.

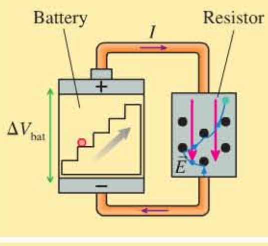
Electric potential

The interaction of charged particles can also be described in terms of an electric potential V.

- Only potential differences ΔV are important.
- If the potential of a particle of charge q changes by ΔV, its potential energy changes by $\Delta U = q\Delta V$.
- Where two equipotential surfaces with potential difference ΔV are separated by distance d, the electric field strength is $E = \Delta V/d$.

Current and circuits

Potential differences ΔV drive current in circuits. Though electrons are the charge carriers in metals, the **current** I is defined to be the motion of positive charges.



- Circuits obey Kirchhoff's loop law (conservation of energy) and Kirchhoff's junction law (conservation of charge).
- The current through a resistor is $I = \Delta V_R/R$. This is **Ohm's law.**

Electromagnetic waves

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

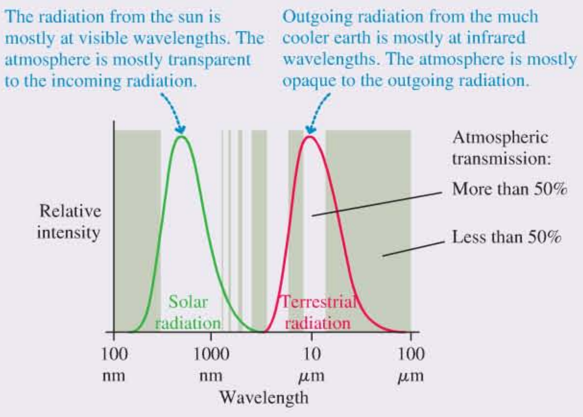
- $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of travel.
- All electromagnetic waves travel at the same speed, c.
- The **electromagnetic spectrum** is the spread of wavelengths and frequencies of electromagnetic waves, from radio waves through visible light to gamma rays.

The Greenhouse Effect and Global Warming

Electromagnetic waves are real, and we depend on them for our very existence; energy carried by electromagnetic waves from the sun provides the basis for all life on earth. Because of the sun's high surface temperature, it emits most of its thermal radiation in the visible portion of the electromagnetic spectrum. As the figure below shows, the earth's atmosphere is transparent to the visible and near-infrared radiation, so most of this energy travels through the atmosphere and warms the earth's surface.

Although seasons come and go, *on average* the earth's climate is very steady. To maintain this stability, the earth must radiate thermal energy—electromagnetic waves—back into space at exactly the same average rate that it receives energy from the sun. Because the earth is much cooler than the sun, its thermal radiation is long-wavelength infrared radiation that we cannot see. A straightforward calculation using Stefan's law finds that the average temperature of the earth should be −18°C, or 0°F, for the incoming and outgoing radiation to be in balance.

This result is clearly not correct; at this temperature, the entire earth would be covered in snow and ice. The measured global average temperature is actually a balmier 15°C, or 59°F. The straightforward calculation fails because it neglects to consider the earth's atmosphere. At visible wavelengths, as the figure shows, the atmosphere has a wide "window" of transparency, but this is not true at the infrared wavelengths of the earth's thermal radiation. The atmosphere lets in the visible radiation from the sun, but the outgoing thermal radiation from the earth sees a much smaller "window." Most of this radiation is absorbed in the atmosphere.



Thermal radiation curves for the sun and the earth. The white and gray bars show regions for which the atmosphere is transparent (white) or opaque (tan) to electromagnetic radiation.

Because it's easier for visible radiant energy to get in than for infrared to get out, the earth is warmer than it would be without the atmosphere. The additional warming of the earth's surface because of the atmosphere is called the **greenhouse effect.** The greenhouse effect is a natural part of the earth's physics; it has nothing to do with human activities, although it's doubtful any advanced life forms would have evolved without it.

The atmospheric gases most responsible for the greenhouse effect are carbon dioxide and water vapor, both strong absorbers of infrared radiation. These **greenhouse gases** are of concern today because humans, through the burning of fossil fuels (oil, coal, and natural gas), are rapidly increasing the amount of carbon dioxide in the atmosphere. Preserved air samples show that carbon dioxide made up 0.027% of the atmosphere before the industrial revolution. In the last 150 years, human activities have increased the amount of carbon dioxide to 0.038%, a 40% increase. By 2050, the carbon dioxide concentration will likely increase to 0.054%, double the pre-industrial value, unless the use of fossil fuels is substantially reduced.

Carbon dioxide is a powerful absorber of infrared radiation. Adding more carbon dioxide makes it even harder for emitted thermal radiation to escape, increasing the average surface temperature of the earth. The net result is **global warming.**

There is strong evidence that the earth has warmed nearly 1°C in the last 100 years because of increased greenhouse gases. What happens next? Climate scientists, using sophisticated models of the earth's atmosphere and oceans, calculate that a doubling of the carbon dioxide concentration will likely increase the earth's average temperature by an additional 2°C (≈3°F) to 6°C (≈9°F). There is some uncertainty in these calculations; the earth is a large and complex system. Perhaps the earth will get cloudier as the temperature increases, moderating the increase. Or perhaps the arctic ice cap will melt, making the earth less reflective and leading to an even more dramatic temperature increase.

But the basic physics that leads to the greenhouse effect, and to global warming, is quite straightforward. Carbon dioxide in the atmosphere keeps the earth warm; more carbon dioxide will make it warmer. How much warmer? That's an important question, one that many scientists around the world are attempting to answer with ongoing research. But large or small, change *is* coming. Global warming is one of the most serious challenges facing scientists, engineers, and all citizens in the 21st century.

PART VI PROBLEMS

The following questions are related to the passage "The Greenhouse Effect and Global Warming" on the previous page.

1. The intensity of sunlight at the top of the earth's atmosphere is approximately 1400 W/m^2. Mars is about 1.5 times as far from the sun as the earth. What is the approximate intensity of sunlight at the top of Mars's atmosphere?
   A. 930 W/m^2
   B. 620 W/m^2
   C. 410 W/m^2
   D. 280 W/m^2
2. Averaged over day, night, seasons, and weather conditions, a square meter of the earth's surface receives an average of 240 W of radiant energy from the sun. The average power radiated back to space is
   A. Less than 240 W.
   B. More than 240 W.
   C. Approximately 240 W.
3. The thermal radiation from the earth's surface peaks at a wavelength of approximately 10 μm. If the surface of the earth warms, this peak will
   A. Shift to a longer wavelength.
   B. Stay the same.
   C. Shift to a shorter wavelength.
4. The thermal radiation from the earth's surface peaks at a wavelength of approximately 10 μm. What is the energy of a photon at this wavelength?
   A. 2.4 eV   B. 1.2 eV
   C. 0.24 eV   D. 0.12 eV
5. Electromagnetic waves in certain wavelength ranges interact with water molecules because the molecules have a large electric dipole moment. The electric field of the wave
   A. Exerts a net force on the water molecules.
   B. Exerts a net torque on the water molecules.
   C. Exerts a net force and a net torque on the water molecules.

The following passages and associated questions are based on the material of Part VI.

Taking an X Ray

X rays are a very penetrating form of electromagnetic radiation. X rays pass through the soft tissue of the body but are largely stopped by bones and other more dense tissues. This makes x rays very useful for medical and dental purposes, as you know.

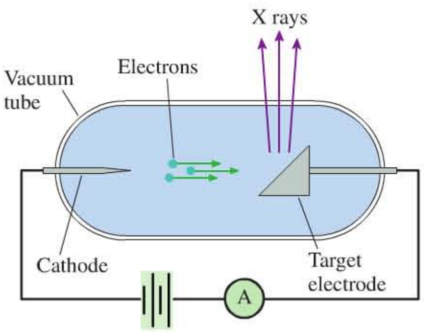


FIGURE VI.1

A schematic view of an x-ray tube and a driver circuit is given in Figure VI.1. A filament warms the cathode, freeing electrons. These electrons are accelerated by the electric field established by a high-voltage power supply connected between the cathode and a metal target. The electrons accelerate in the direction of the target. The rapid deceleration when they strike the target generates x rays. Each electron will emit one or more x rays as it comes to rest.

An x-ray image is essentially a shadow; x rays darken the film where they pass, but the film stays unexposed, and thus light, where bones or dense tissues block x rays. An x-ray technician adjusts the quality of an image by adjusting the energy and the intensity of the x-ray beam. This is done by adjusting two parameters: the accelerating voltage and the current through the tube. The accelerating voltage determines the energy of the x-ray photons, which can't be greater than the energy of the electrons. The current through the tube determines the number of electrons per second and thus the number of photons emitted. In clinical practice, the exposure is characterized by two values: "kVp" and "mAs." kVp is the peak voltage in kV. The value mAs is the product of the current (in mA) and the time (in s) to give a reading in mA·s. This is a measure of the total number of electrons that hit the target and thus the number of x rays emitted.

Typical values for a dental x ray are a kVp of 70 (meaning a peak voltage of 70 kV) and mAs of 7.5 (which comes from a current of 10 mA for 0.75 s, for a total of 7.5 mAs). Assume these values in all of the problems that follow.

6. In Figure VI.1, what is the direction of the electric field in the region between the cathode and the target electrode?
   A. To the left
   B. To the right
   C. Toward the top of the page
   D. Toward the bottom of the page
7. If the distance between the cathode and the target electrode is approximately 1.0 cm, what will be the maximum acceleration of the free electrons? Assume that the electric field is uniform.
   A. 1.2×10^{18} m/s^2 B. 1.2×10^{16} m/s^2
   C. 1.2×10^{15} m/s^2 D. 1.2×10^{12} m/s^2
8. What, physically, does the product of a current (in mA) and a time (in s) represent?
   A. Energy in mJ
   B. Potential difference in mV
   C. Charge in mC
   D. Resistance in mΩ
9. During the 0.75 s that the tube is running, what is the electric power?
   A. 7.0 kW   B. 700 W
   C. 70 W   D. 7.0 W
10. If approximately 1% of the electric energy ends up in the x-ray beam (a typical value), what is the approximate total energy of the x rays emitted?
    A. 500 J   B. 50 J
    C. 5 J   D. 0.5 J
11. What is the maximum energy of the emitted x-ray photons?
    A. 70×10^3 J   B. 1.1×10^{-11} J
    C. 1.1×10^{-14} J   D. 1.6×10^{-18} J

Electric Cars

In recent years, practical hybrid cars have hit the road—cars in which the gasoline engine runs a generator that charges batteries that run an electric motor. These cars offer increased efficiency, but significantly greater efficiency could be provided by a purely electric car run by batteries that you charge by plugging into an electric outlet in your house.

But there's a practical problem with such vehicles: the time necessary to recharge the batteries. If you refuel your car with gas at the pump, you add 130 MJ of energy per gallon. If you add 20 gallons, you add a total of 2.6 GJ in about 5 minutes. That's a lot of energy in a short time; the electric system of your house simply can't provide power at this rate.

There's another snag as well. Suppose there were electric filling stations that could provide very high currents to recharge your electric car. Conventional batteries can't recharge very quickly; it would still take longer for a recharge than to refill with gas.

One possible solution is to use capacitors instead of batteries to store energy. Capacitors can be charged much more quickly, and as an added benefit, they can provide energy at a much greater rate—allowing for peppier acceleration. Today's capacitors can't store enough energy to be practical, but future generations will.

12. A typical home's electric system can provide 100 A at a voltage of 220 V. If you had a charger that ran at this full power, approximately how long would it take to charge a battery with the equivalent of the energy in one gallon of gas?
    A. 100 min B. 50 min
    C. 20 min D. 5 min
13. The Tesla Roadster, a production electric car, has a 375 V battery system that can provide a power of 200 kW. At this peak power, what is the current supplied by the batteries?
    A. 75 kA B. 1900 A
    C. 530 A D. 75 A
14. To charge the batteries in a Tesla Roadster, a transformer is used to step up the voltage of the household supply. If you step a 220 V, 100 A system up to 400 V, what is the maximum current you can draw at this voltage?
    A. 180 A B. 100 A
    C. 55 A D. 45 A
15. One design challenge for a capacitor-powered electric car is that the voltage would change with time as the capacitors discharge. If the capacitors in a car were discharged to half their initial voltage, what fraction of energy would still be left?
    A. 75% B. 67%
    C. 50% D. 25%

Wireless Power Transmission

Your laptop has wireless communications connectivity, and you might even have a wireless keyboard or mouse. But there's one wire you haven't been able to get rid of yet—the power cord.

Researchers are working on ways to circumvent the need for a direct electrical connection for power, and they are experiencing some success. Recently, investigators were able to use current flowing through a primary coil to power a 60 W lightbulb connected to a secondary coil 2.0 m away, with approximately 15% efficiency. The coils were large and the efficiency low, but it's a start.

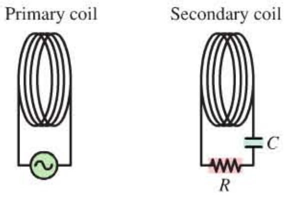


FIGURE VI.2

The wireless power transfer system is outlined in Figure VI.2. An AC supply generates a current through the primary coil, creating a varying magnetic field. This field induces a current in the secondary coil, which is connected to a resistance (the lightbulb) and a capacitor that sets the resonance frequency of the secondary circuit to match the frequency of the primary circuit.

16. At a particular moment, the current in the primary coil is clockwise, as viewed from the secondary coil. At the center of the secondary coil, the field from the primary coil is
    A. To the right.
    B. To the left.
    C. Zero.
17. At a particular moment, the magnetic field from the primary coil points to the right and is increasing in strength. The field due to the induced current in the secondary coil is
    A. To the right.
    B. To the left.
    C. Zero.
18. The power supply drives the primary coil at 9.9 MHz. If this frequency is doubled, how must the capacitor in the secondary circuit be changed?
    A. Increase by a factor of 2
    B. Increase by a factor of $\sqrt{2}$
    C. Decrease by a factor of 2
    D. Decrease by a factor of 4
19. What are the rms and peak currents for a 60 W bulb? (The rms voltage is the usual 120 V.)
    A. 0.71 A, 0.71 A B. 0.71 A, 0.50 A
    C. 0.50 A, 0.71 A D. 0.50 A, 0.50 A

Additional Integrated Problems

20. A 20 Ω resistor is connected across a 120 V source. The resistor is then lowered into an insulated beaker, containing 1.0 L of water at 20° C, for 60 s. What is the final temperature of the water?
21. As shown in Figure VI.3, a square loop of wire, with a mass of 200 g, is free to pivot about a horizontal axis through one of its sides. A 0.50 T horizontal magnetic field is directed as shown. What current I in the loop, and in what direction, is needed to hold the loop steady in a horizontal plane?

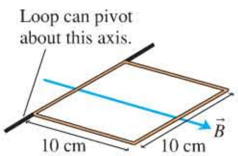


FIGURE VI.3