CHAPTER 13

Electromagnetic Waves

Electric and magnetic fields are so intimately related that each can create the other even in empty space. In fact, the two fields can form electromagnetic waves, in which they recreate one another endlessly and head off across space at an enormous speed. These electromagnetic waves are all around us and are the basis for much of our communications technology, for radiative heat transfer, and for our ability to see the universe in which we live.

EXPERIMENT: A Disc in the Microwave Oven

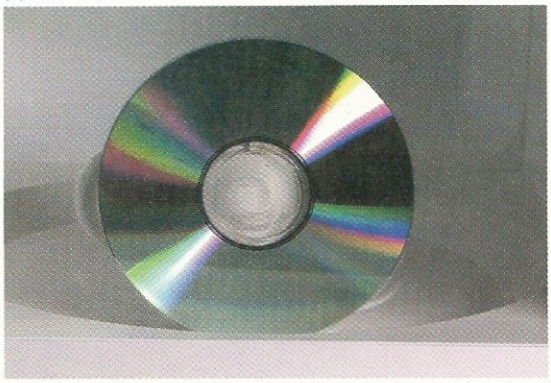
You can experiment with electromagnetic waves using a microwave oven. As we'll see in Section 13.2, microwaves are a type of electromagnetic wave that falls between radio waves and light. Because electromagnetic waves consist of electric and magnetic fields, they can propel electric currents through metal objects. Those currents can do some interesting things.

In this experiment, you'll put metal in a microwave oven. There is always some risk associated with that activity, so if you cannot fully accept that risk yourself, skip this experiment and look at the photographs instead. If you're young enough to require adult supervision or consent, obtain it or skip the experiment.

If you choose to conduct this experiment, make sure that there is nothing flammable in or near the oven and that the area around you is well ventilated. The plastic in the disc will heat up and release a mildly unpleasant smell that will dissipate. Do not leave the oven on for more than 4 seconds or that smell will become truly unpleasant.

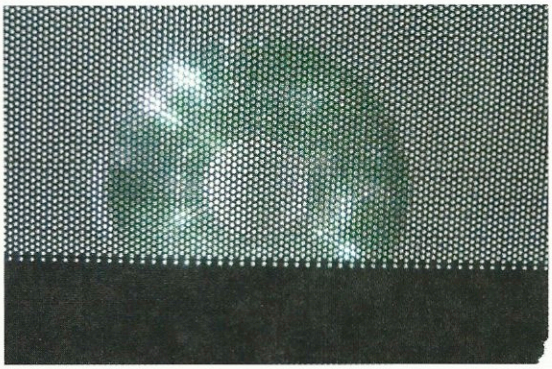
The metal for this experiment is the ultrathin reflective film located inside a CD or DVD. Although that metal layer's electrical conductivity makes it reflective, it wasn't

(a)



Courtesy Lou Bloomfield

(b)



designed to carry large electric currents. When exposed to the microwave electric fields in the oven, that metal will carry large currents, heat up, tear, and spark.

To perform the experiment, you'll need a CD or DVD that you are comfortable destroying. Place a microwave-safe ceramic mug near the center of the microwave oven. Lean the CD or DVD against the mug so that you can see the disc's shiny face through the oven door. If the oven has a rotating tray, you may want to remove that tray temporarily for the experiment. You may also want to block the oven's light temporarily with black tape. Be sure that you replace the tray and unblock the light when you're done.

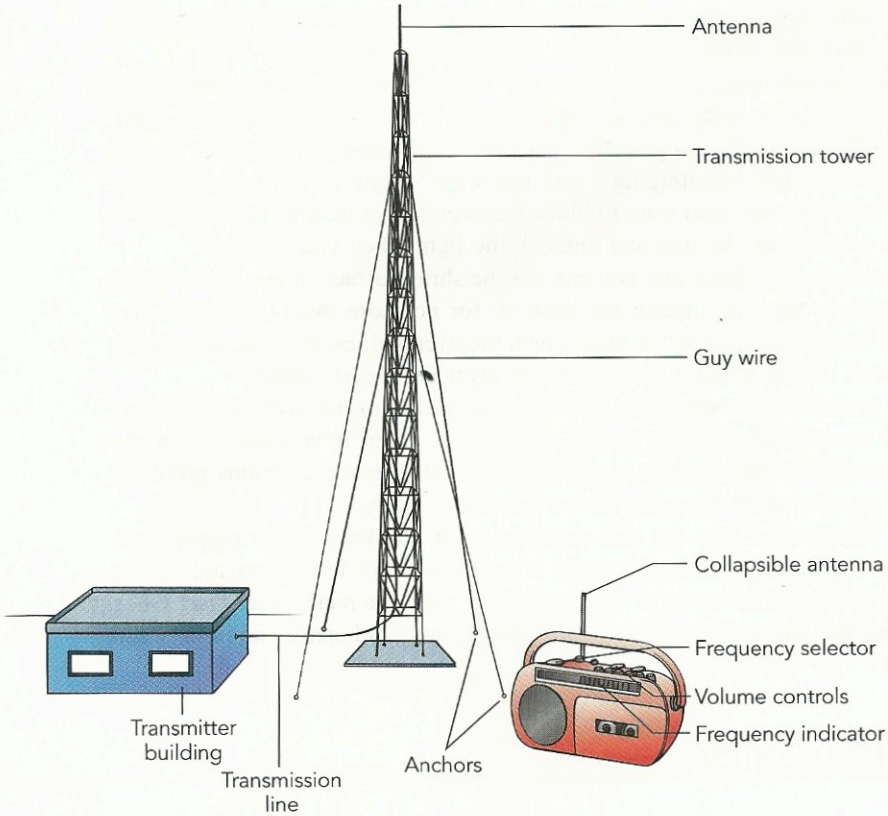
Close the oven door and check that you can see the shiny surface of the CD or DVD clearly. Now prepare to turn the microwave oven on for no more than 4 seconds. You should know what to expect: 2 seconds during which the oven will build up its microwave power and 2 seconds during which the disc's metal layer will spark wildly.

When you're prepared and everything is safely arranged, turn the oven on for 4 seconds. You should see lots of sparking in that metal layer. Even if you don't, turn the oven off after 4 seconds or the overheated plastic smell will become a serious problem. Let the disc cool and the smell dissipate. Discard the disc safely.

Why did the microwaves heat the thin metal layer in the disc? What happened to the temperature of the plastic disc as the metal layer heated up? Which expands faster with increasing temperature: the metal or the plastic? Why did the metal layer tear? Once the metal layer had fragmented into many sharp islands, why did sparks jump between those islands?

Chapter Itinerary

In this chapter, we'll discuss how electromagnetic waves are formed and detected in two common situations: (1) *radio* and (2) *microwave ovens*. In *radio*, we'll examine the ways in which charge moving in an antenna can emit or respond to electromagnetic waves and how those waves can be controlled in order to send an audio signal from a radio transmitter to a radio receiver. In *microwave ovens*, we'll see how microwaves affect water molecules and metals, and also how they are produced in the oven's magnetron tube. Although we can't see the electromagnetic waves that these two devices use, they clearly play important roles in our world. For more about what we'll study, turn to the Chapter Summary at the end of the chapter.



SECTION 13.1 Radio

We've seen that electric currents can represent sound and carry speech and music anywhere wires will reach, but how can we send sound to someone who is moving? We need a way to represent sound that doesn't involve wires. We need radio.

This section describes how radio works. We'll look at how radio waves are transmitted and how they're received. We'll also examine the common ways in which sound is represented by radio waves so that it can travel through space to a receiver far away.

Questions to Think About: *How might the movement of electric charge in one metal antenna affect electric charge in a second antenna nearby? What about when the second antenna is far away from the first antenna? What does it mean when a radio station claims to transmit 50,000 watts? How does your radio select one channel from among all the possibilities?*

Experiments to Do: *Listen to a small AM radio and notice that the volume of the sound depends on the radio's orientation or location. Radio waves are pushing electric charges back and forth along the radio's hidden internal antenna. You can sometimes find an orientation in which the radio is silent because in that orientation the radio waves are unable to move charges along the antenna. If you put the radio inside a metal box, it will also become silent. Can you explain why?*

You can try similar experiments with a cordless telephone—actually a radio transmitter and receiver. See how far you can go with the handset before you lose contact with the base unit. Notice that the antenna's size and orientation affect its range. What happens to the reception if you stand behind a large metal object?

A Prelude to Radio Waves

Before we can examine radio and radio waves, let's take a moment to finish the introduction to electrodynamics that we began in Chapters 10 and 11. Although we've already learned most of the fundamental relationships between electricity and magnetism, the remaining one is about to become important. To refresh your memory, we have observed so far that electric fields can be produced by electric charges and by changing magnetic fields and that magnetic fields can be produced by moving electric charges (Table 13.1.1).

In 1865, Scottish physicist James Clerk Maxwell (1831–1879) discovered a second source of magnetic fields: *changing electric fields*. That effect is subtle, and scientists overlooked it for most of the nineteenth century. It wasn't until Maxwell was trying to formulate a complete electromagnetic theory that he uncovered this additional connection between electricity and magnetism. This final relationship completed the set shown in Table 13.1.1. Together, these relationships allowed Maxwell to understand one of the most remarkable phenomena in nature: electromagnetic waves!

Third Connection between Electricity and Magnetism
Electric fields that change with time produce magnetic fields.

Since electric fields can create magnetic fields and magnetic fields contain energy, it's clear that electric fields must contain energy, too. The amount of energy in a uniform electric field is the square of the field strength times the volume of the field divided by 8π times the Coulomb constant. We can write this relationship as a word equation:

$$\text{energy} = \frac{\text{electric field}^2 \cdot \text{volume}}{8\pi \cdot \text{Coulomb constant}}, \tag{13.1.1}$$

in symbols:

$$U = \frac{E^2 \cdot V}{8\pi \cdot k},$$

and in everyday language:

When you charge a large capacitor, it stores a great deal of energy in the electric field between its plates.

With these observations, we have finished the prelude and are ready to see how radio works.

Table 13.1.1 Sources of Electric and Magnetic Fields

SOURCES OF ELECTRIC FIELDS	SOURCES OF MAGNETIC FIELDS
Electric charge	Moving electric charge
Changing magnetic fields	Changing electric fields

Check Your Understanding #1: A Real Flux Capacitor

When a capacitor has separated charge on its plates, there is a strong electric field between those plates. Connecting the plates with a wire will discharge the capacitor and its electric field will suddenly vanish. As the electric field disappears, what other field is present between the plates?

Answer: There is now a magnetic field between the plates.

Why: Since a changing electric field produces a magnetic field, the plates have a magnetic field between them while their electric field is disappearing.

Check Your Figures #1: Lightning in the Fields

During a thunderstorm, the charged clouds produce an electric field of about 10,000 V/m near the ground. How much energy is contained in 1.0 cubic meter of that electric field?

Answer: The electric field in 1.0 cubic meter is about 0.00045 J.

Why: Since 10,000 V/m is equivalent to 10,000 J/C · m, Eq. 13.1.1 gives us the energy of a 10,000 V/m field occupying 1.0 m^3 as:

$$\text{energy} = \frac{(10{,}000\ \text{J/C} \cdot \text{m})^2 \cdot 1.0\ \text{m}^3}{8\pi \cdot 8.988 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2} = \frac{0.00045\ \text{J}^2}{\text{N} \cdot \text{m}} = 0.00045\ \text{J}.$$

While that isn't much energy per cubic meter, a single lightning strike may release the electric field energy in almost a billion cubic meters. No wonder it produces such a bang!

Antennas and Tank Circuits

A radio transmitter communicates with a receiver via radio waves. These waves are produced by electric charge as it moves up and down the transmitter's antenna and are detected when they push electric charge up and down the receiver's antenna. What exactly are radio waves, and how does charge on the antenna produce them?

We've already seen that electric charge produces electric fields and that moving charge produces magnetic fields. However, something new happens when charge *accelerates*. Accelerating charge produces a mixture of changing electric and magnetic fields that can reproduce one another endlessly and travel long distances through empty space. These interwoven electric and magnetic fields are known generally as **electromagnetic waves**. In the case of radio, the electromagnetic waves have low frequencies and long wavelengths and are known as **radio waves**.

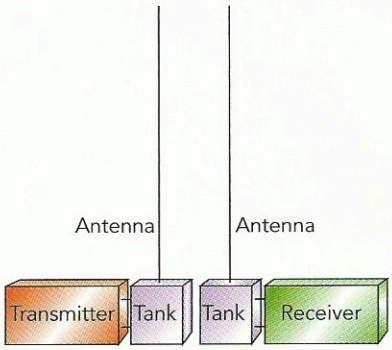


Fig. 13.1.1 Electric charge rushing on and off the transmitting antenna causes a similar motion of electric charge in the receiving antenna.

Before we look at the structure of a radio wave and at how it travels through space let's start with a much simpler situation. We'll look at how two nearby metal antenna affect one another. Figure 13.1.1 shows a radio transmitter and a radio receiver, side b side. Because of their proximity, electric charge on the transmitter's antenna is sure affect charge on the receiver's antenna.

To communicate with the nearby receiver, the transmitter sends charge up and down its antenna. This charge's electric field surrounds the transmitting antenna and extends all the way to the receiving antenna, where it pushes charge down and up. Unfortunately, the resulting charge motion in the receiving antenna is weak, and the receiver may have difficulty distinguishing it from random thermal motion or from motion caused by other electric fields in the environment. Therefore the transmitter adopts a clever strategy—it moves charge up and down its antenna rhythmically at a particular frequency. Since the resulting motion on the receiving antenna is rhythmic at that same frequency, it's much easier for the receiver to distinguish from unrelated motion.

Using this rhythmic motion has another advantage: it allows the transmitter and receiver to each use a **tank circuit**—a resonant electronic circuit consisting only of a capacitor and an inductor (Fig. 13.1.2). Charge "sloshes" back and forth through the tank circuit at a particular frequency, much as a child swings back and forth on a swing. Just as you can get a child swinging strongly at the playground by giving her a gentle push every swing, so the transmitter can make charge slosh strongly through its tank circuit by giving that charge a gentle push every cycle. By helping the transmitter move larger amounts of charge up and down the antenna, the tank circuit dramatically strengthens the transmission.

A second tank circuit attached to the receiving antenna helps the receiver detect this transmission. Gentle, rhythmic pushes by fields from the transmitting antenna cause more and more charge to move through the receiving antenna and its attached tank circuit. While the motion of charge on this antenna alone may be difficult to detect, the much larger charge sloshing in the tank circuit is unmistakable.

We can understand how a tank circuit works by looking at how charge moves between its capacitor and its inductor. Let's imagine that the tank circuit starts out with separated charge on the plates of its capacitor (Fig. 13.1.2*a*). Since the inductor conducts electricity, current begins to flow from the positively charged plate, through the inductor, to the negatively charged plate. The current through the inductor must rise slowly and, as it does, it creates a magnetic field in the inductor (Fig. 13.1.2*b*).

Soon the capacitor's separated charge is gone, and all of the tank circuit's energy is stored in the inductor's magnetic field (Fig. 13.1.2*c*). However, the current keeps flowing, driven forward by the inductor's opposition to current changes. The inductor uses the energy in its magnetic field to keep the current flowing, and separated charge reappears in the capacitor (Fig. 13.1.2*d*). Eventually, the inductor's magnetic field decreases to zero, and everything is back to its original state—almost. While all of the tank circuit's energy has returned to the capacitor, the separated charge in that capacitor is now upside down (Fig. 13.1.2*e*).

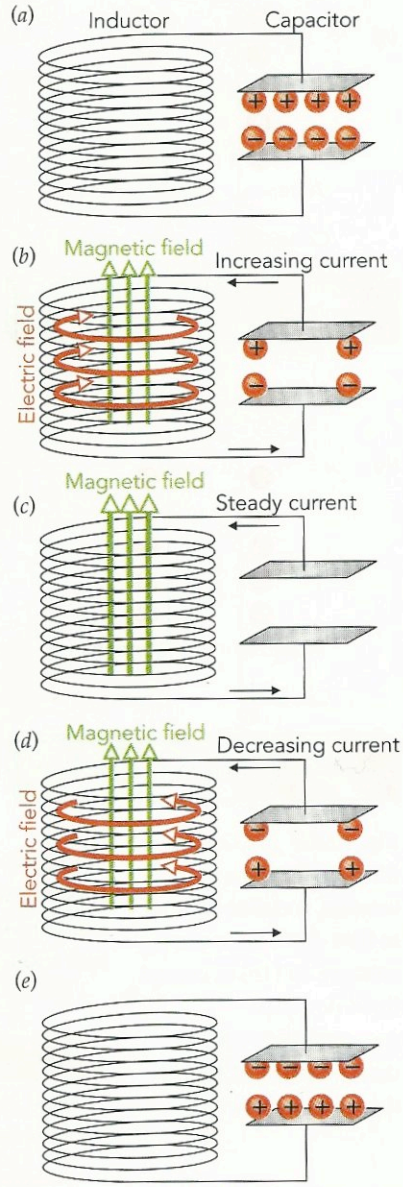


Fig. 13.1.2 A tank circuit consists of a capacitor and an inductor. Energy sloshes rhythmically back and forth between the two components.

This whole process now repeats in reverse. The current flows backward through the inductor, magnetizing it upside down, and the tank circuit soon returns to its original state. This cycle repeats over and over again, with charge sloshing from one side of the capacitor to the other and back again.

A tank circuit is an electronic harmonic oscillator, equivalent to the mechanical harmonic oscillators we examined in Chapter 9. Like all harmonic oscillators, its period (the time per cycle) doesn't depend on the amplitude of its oscillation. Thus no matter how much charge is sloshing in the tank circuit, the time it takes that charge to flow over and back is always the same.

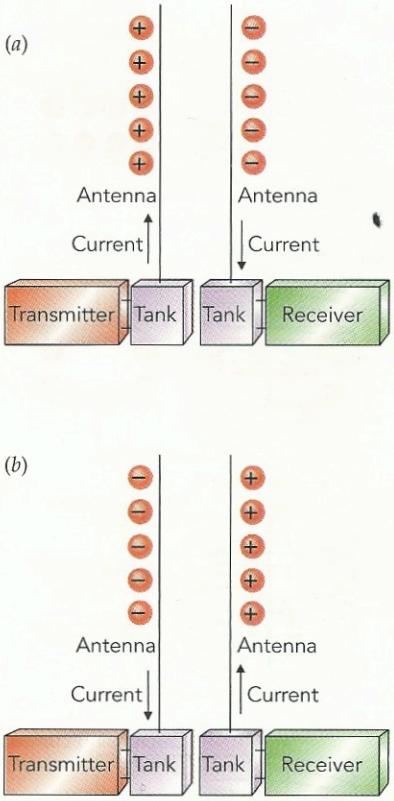


Fig. 13.1.3 (*a*) As current flows up the transmitting antenna, it causes current to flow down the receiving antenna, and (*b*) as current flows down the transmitting antenna, it causes current to flow up the receiving antenna.

The tank circuit's period depends only on its capacitor and its inductor. The larger the capacitor's capacitance, the more separated charge it can hold with a given amount of energy and the longer it takes that charge to move through the circuit as current. The larger the inductor's **inductance**—its opposition to current changes—the longer that current takes to start and stop. A tank circuit with a large capacitor and a large inductor may have a period of a thousandth of a second or more, while one with a small capacitor and a small inductor may have a period of a billionth of a second or less.

Inductance is defined as the voltage drop across the inductor divided by the rate at which current through the inductor changes with time. This division gives inductance the units of voltage divided by current per time. The SI unit of inductance is the volt-second-per-ampere, also called the **henry** (abbreviated H). While large electromagnets have inductances of hundreds of henries, a 1-μH (0.000001-H) inductor is more common in radio.

Its resonant behavior makes the tank circuit useful in radio. That's because small, rhythmic pushes on the current in a tank circuit can lead to enormous charge oscillations in that circuit. In radio, these rhythmic pushes begin when the transmitter sends an alternating current through a coil of wire. Fields from this coil push current back and forth through the nearby transmitting tank circuit, causing enormous amounts of charge to slosh back and forth in it and travel up and down the transmitting antenna. That charge's electric field then pushes rhythmically on charge in the receiving antenna, causing substantial amounts of charge to travel down and up it and slosh back and forth in the receiving tank circuit (Fig 13.1.3). The receiver can easily detect this sloshing charge.

Energy flows from the transmitter to the receiver via resonant energy transfer: from the transmitter, to the transmitting tank circuit and antenna, to the receiving antenna and tank circuit, and finally to the receiver. This sequence of transfers can work efficiently only if all the parts have resonances at the same frequency. Tuning a radio receiver to a particular station is largely a matter of adjusting its capacitor and inductor so that its tank circuit has the right resonant frequency.

Check Your Understanding #2: No Tanks

Why doesn't the radio transmitter simply push electric charge directly on and off the antenna, without using a tank circuit?

Answer: The amount of charge that the transmitter can move directly on and off the antenna is too small to create a strong radio signal.

Why: The tank circuit is useful because it allows the transmitter to move much more charge. Just as a tuning fork is inefficient at emitting sound waves by itself, so a radio antenna is inefficient at emitting radio waves by itself. You can make the tuning fork much louder by coupling it to an object that resonates at its frequency. Similarly, you can make the radio antenna emit a much stronger radio wave by coupling it to a tank circuit that resonates at its frequency.

Radio Waves

When the two antennas are close together, charge in the transmitting antenna simply exerts electrostatic force on charge in the receiving antenna. However, when the antennas are far apart, the interactions between them are more complicated. Charge in the

transmitting antenna must then emit a radio wave in order to push on charge in the receiving antenna. Like a water wave, a radio wave is a disturbance that carries energy from one place to another. But unlike a water wave, which must travel in a fluid, a radio wave can travel through otherwise empty space, from one side of the universe to the other.

Like all electromagnetic waves, a radio wave consists only of a changing electric field and a changing magnetic field. These fields recreate one another over and over again as the wave travels through empty space at the speed of light—exactly 299,792,458 m/s (approximately 186,282 miles-per-second).

The radio wave is created when electric charge in the antenna accelerates. Whereas stationary charge or a steady current produces constant electric or magnetic fields, accelerating charge produces fields that change with time. As charge flows up and down the antenna, its electric field points alternately up and down, and its magnetic field points alternately left and right. These changing fields then recreate one another again and again and sail off through space as an electromagnetic wave.

The wave emitted by a vertical transmitting antenna has a **vertical polarization**—that is, its electric field points alternately up and down (Fig. 13.1.4*a*). We identify those "ups" as crests, and the distance between adjacent crests is its wavelength. For radio waves, that wavelength is usually 1 m (3.3 ft) or more. The wave's magnetic field is perpendicular to its electric field and thus points alternately left and right.

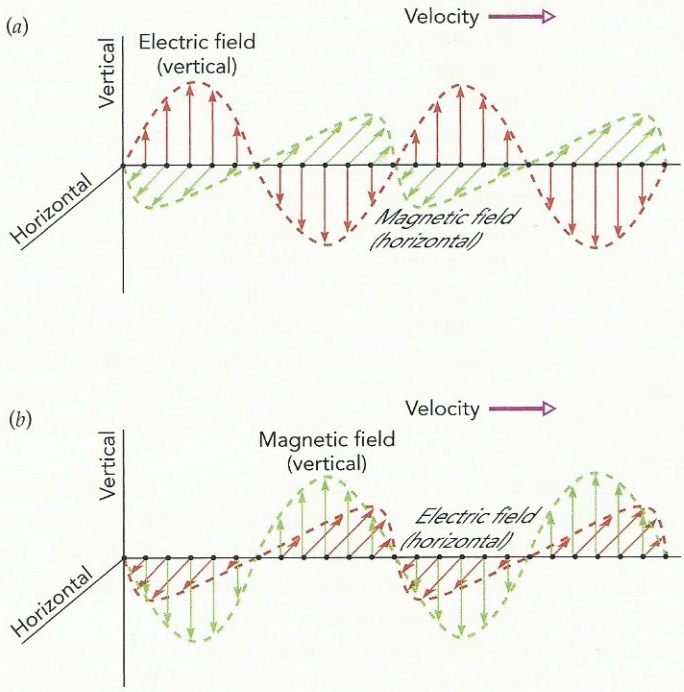


Fig. 13.1.4 (*a*) In a vertically polarized electromagnetic wave, the electric field along the wave's level path points alternately up and down, while the magnetic field along that path points alternately right and left. Each vertical arrow indicates the electric field at the point marked by the dot, and each horizontal arrow indicates the magnetic field at that point. (*b*) In a horizontally polarized wave, the electric field along the wave's level path points alternately left and right, while the magnetic field points alternately up and down. Each vertical arrow indicates the magnetic field at the point marked by the dot, and each horizontal arrow indicates the electric field at that point. Both waves are heading to the right at the speed of light.

Had the transmitting antenna been tipped on its side, the wave's electric field would have pointed alternately left and right and the wave would have had a **horizontal polarization** (Fig. 13.1.4*b*). The wave's magnetic field would then point alternately up and down. Whatever the polarization, the electric and magnetic fields move forward together as a traveling wave, so the pattern of fields moves smoothly through space at the speed of light.

Common Misconceptions: Electromagnetic Waves and Undulations

Misconception: Since the fields of an electromagnetic wave appear wavy (Fig. 13.1.4), the light wave itself undulates; it actually undulates up and down or back and forth as it heads rightward!

Resolution: The arrows drawn to represent the fields in an electromagnetic wave are associated with points along the straight axis of the wave. Each wave in Fig. 13.1.4 is heading directly rightward along the axis line, and the arrows indicate field values at points along that line.

If you stood in one place and watched this wave pass, you'd notice its electric field fluctuating up and down at the same frequency as the charge that created it. When the wave passes a distant receiving antenna, it pushes charge up and down that antenna at this frequency. If the receiving tank circuit is resonant at this frequency, the amount of charge sloshing in it should become large enough for the receiver to detect.

A radio station can optimize its transmission by using a transmitting antenna of the proper length. When that length is exactly a quarter of the wavelength of the radio wave it's transmitting, charge sloshes vigorously up and down the antenna in a natural resonance. Surprisingly enough, the antenna is another electronic harmonic oscillator, with a period that depends only on its length. (In fact, the antenna is the top half of a tank circuit, with its tip acting as one plate of a capacitor and its length acting as the top half of an inductor. Objects at the base of the antenna complete the tank circuit.) When the transmitting tank circuit and antenna have resonances at the same frequency, there's a resonant energy transfer from one to the other. As you might expect, these resonant effects help to produce a powerful radio wave.

The transmitting antenna sends the strongest portion of its radio wave out perpendicular to its length. That's not unexpected, because the motion of charge on the antenna is most obvious when viewed from a line perpendicular to its length. Thus a vertical antenna sends most of its wave out horizontally, where people are likely to receive it. No wave emerges from the ends of an antenna.

Both electric and magnetic fields contain energy, so as the electromagnetic wave travels through space, it carries energy away from the transmitter. When a radio station advertises that it "transmits 50,000 watts of music," it's claiming that its antenna emits 50,000 J of energy per second or 50,000 W of power in its electromagnetic wave. The receiving antenna must absorb enough of this power to detect the wave. However, the farther the wave gets from the transmitting antenna, the more spread out and weak it becomes. Trees and mountains also absorb or reflect some of the wave and hinder reception.

For the best reception, a listener should be located where the radio wave is strong and where there's an unobstructed path from the transmitting antenna to the receiving antenna. The receiving antenna should be a quarter-wavelength long, and it should be oriented along the radio wave's polarization—vertical for a vertically polarized radio

wave or horizontal for a horizontally polarized radio wave. Aligning the receiving antenna with the wave's polarization makes certain that the wave's electric field pushes charge *along* the antenna, not *across* it.

To ensure good reception regardless of receiving antenna orientation, many radio stations transmit a complicated *circularly polarized* wave that combines both vertical and horizontal polarizations. To form this wave, they need several quarter-wavelength antennas. For wavelengths under a few meters, these antennas can all be attached inexpensively to a single mast. That's why commercial FM and TV broadcasts, which use short-wavelength radio waves, are usually transmitted with circular polarization. However, commercial AM broadcasts, which use long-wavelength radio waves, are transmitted only with vertical polarization.

Because commercial FM radio waves usually include both polarizations, FM receiving antennas can be vertical or horizontal. Portable FM receivers often use vertical telescoping antennas, while home receivers frequently use horizontal wire antennas. All of these antennas are roughly a quarter-wavelength long.

A quarter-wavelength antenna for commercial AM radio would have to be about 100 m (330 ft) long, so straight AM antennas (such as those on cars) are much shorter than optimal. That's why many AM antennas are designed to respond to the radio wave's horizontal magnetic field rather than to its vertical electric field. These magnetic antennas are horizontal coils of wire that experience induced currents when exposed to fluctuating magnetic fields.

Check Your Understanding #3: There's No Place Like Home

Why do cordless telephones only work when they're close to their base units?

Answer: When the cordless telephone is too far from its base unit, the electromagnetic waves become so spread out that they have trouble communicating.

Why: The powers emitted by the base unit and the handset are small, so that their waves are relatively difficult to detect. As long as the handset and base unit are nearby, they are able to detect each other's waves. When the distance between them becomes too great, the waves become too spread out to detect, and the handset and base unit lose contact with one another.

Representing Sound: AM and FM Radio

A radio transmitter does more than simply emit a radio wave. It uses that radio wave to *represent sound*. Because sound waves are fluctuations in air density and radio waves are fluctuations in electric and magnetic fields, a radio wave can't literally "carry" a sound wave. However, a radio wave can carry sound information and instruct the receiver how to reproduce the sound.

To convey sound information, the radio station alters its radio wave to represent compressions and rarefactions of the air. The receiver then recreates those compressions and rarefactions. There are two common techniques by which a radio wave can represent those density fluctuations. One is called amplitude modulation and involves changing the overall strength of the radio wave. The other is called frequency modulation and involves small changes in the frequency of the radio wave.

In the **amplitude modulation** (AM) technique, air density is represented by the strength of the transmitted wave (Fig. 13.1.5). To represent a compression of the air, the transmitter is turned up so that more charge moves up and

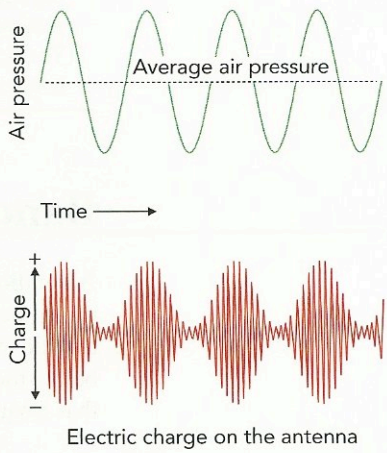


Fig. 13.1.5 When sound is transmitted using amplitude modulation, air pressure is represented by the strength of the radio wave. A compression is represented by strengthening the radio wave, and a rarefaction is represented by weakening it.

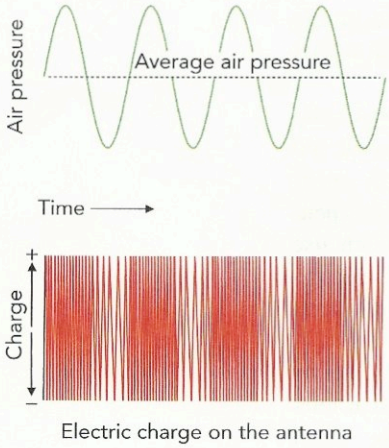


Fig. 13.1.6 When sound is transmitted by frequency modulation, air pressure is represented by changing the frequency of the radio transmitter slightly. A compression is represented by increasing that frequency and a rarefaction by decreasing it.

down the transmitting antenna. To represent a rarefaction, the transmitter is turned down so that less charge moves up and down the antenna.

The frequency at which charge moves up and down the antenna remains steady, so only the amplitude of the radio wave changes. The receiver measures the strength of the radio wave and uses this measurement to recreate the sound. When it detects a strong radio wave, it pushes its speaker toward the listener and compresses the air. When it detects a weak radio wave, it pulls its speaker away from the listener and rarefies the air.

In the **frequency modulation** (FM) technique, air density is represented by the frequency of the transmitted wave (Fig. 13.1.6). To represent a compression of the air, the transmitter's frequency is increased slightly so that charge moves up and down the transmitting antenna a little *more* often than normal. To represent a rarefaction, the transmitter's frequency is decreased slightly so that the charge moves up and down a little *less* often than normal. These changes in frequency are extremely small—so small that charge continues to slosh strongly in all the resonant components and reception is unaffected. The receiver measures the radio wave's frequency and uses this measurement to recreate the sound. When it detects an increased frequency it compresses the air, and when it detects a decreased frequency it rarefies the air.

Although the AM and FM techniques for representing sound can be used with a radio wave at any frequency, the most common commercial bands in the United States are the AM band between 550 kHz and 1600 kHz (550,000 Hz and 1,600,000 Hz) and the FM band between 88 MHz and 108 MHz (88,000,000 Hz and 108,000,000 Hz). Elsewhere in the spectrum of radio frequencies are many other commercial, military, and public transmissions, including TV, short wave, amateur radio, telephone, police, and aircraft bands. These other transmissions use AM, FM, and a few other techniques to represent sound and information with radio waves.

Check Your Understanding #4: Another Volume Control

When you are listening to the AM radio in a car and drive through a tunnel, the volume becomes very low. Explain.

Answer: The tunnel blocks most of the radio wave. Since only a small fluctuating wave reaches your radio, the radio produces only small fluctuations in air density with its speaker.

Why: An AM radio has trouble distinguishing between a distant transmission representing loud music and a nearby transmission representing soft music. In both cases, the receiver detects only small variations in the current moving up and down its antenna. That's why you must turn up the volume of an AM radio as you move farther from the transmitting antenna or as you enter a tunnel.

Bandwidth and Cable

An audio signal on a wire has a range of frequencies present in it, from zero frequency up to the highest pitch sound it is representing. Similarly, an audio signal traveling via a radio wave has a range of radio frequencies present in it, stretching from somewhat below the official frequency of the radio wave, the *carrier frequency*, to somewhat above that frequency. The wider the audio frequency range of the sound, the more sound infor-

mation must be sent each second and the wider the range of radio frequencies needed to represent that sound. The range of frequencies needed to transmit such a stream of information is known as the transmission's **bandwidth**.

By international agreement, an AM radio station may use 10 kHz of bandwidth, 5 kHz above and below its carrier frequency. To stay within that bandwidth, the audio signal can't contain frequencies above 5 kHz. Although this restricted frequency range is bad for music, it allows competing stations to function with carrier frequencies only 10 kHz apart, so that 106 different stations can operate between 550 kHz and 1600 kHz.

An FM radio station may use 200 kHz of bandwidth, 100 kHz on each side of its carrier frequency. This luxurious allocation permits FM radio to represent a very broad range of audio frequencies, in stereo, which is why an FM radio station can do a much better job of sending music to your radio than an AM station can.

Because high-frequency radio waves travel in straight lines between antennas, it's hard to receive a commercial FM station from more than about 100 km (60 mi) away. Even when the transmitting antenna sits on top of a tall tower, the earth's curvature and surface terrain severely limit the range of FM reception.

Low-frequency radio waves, such as those used by commercial AM stations, are reflected by charged particles in the earth's outer atmosphere, so portions of the radio wave that would otherwise be lost to space bounce back toward the ground. This returning power allows you to receive AM stations over a considerable distance, even when you have no direct line of sight to the transmitter's antenna. At sundown, these atmospheric layers become so effective at reflecting AM radio that you can hear a transmission from thousands of kilometers away as clearly as if it were a hometown station.

The spectrum of electromagnetic waves is a limited resource and if it could only be used once, it would quickly run out of bandwidth. Fortunately, distance and enclosures make it possible to reuse the spectrum many times. Cell phones that are far from one another can share the same carrier frequencies and bandwidth because their radio waves weaken with distance and essentially don't overlap. However, even nearby radio transmissions can use the same carrier frequencies by enclosing their electromagnetic waves inside cables.

Cable radio, television, and data networks are similar to broadcast networks except that they send electromagnetic waves through cables rather than through empty space. A typical radio or television cable consists of an insulated metal wire inside a tube of metal foil or woven metal mesh. This wire-inside-a-tube arrangement is called *coaxial cable* because its two metal components share the same centerline or axis. In contrast, a typical computer-data cable consists of a number of insulated metal wires that are twisted into several pairs.

Electromagnetic waves can propagate easily through a coaxial or twisted-pair cable, following its twists and turns from the transmitter that produces the waves to the receiver that uses them. The fact that wires are assisting these waves in their travels makes them more complicated than waves in empty space. However, they still involve electric and magnetic fields and still propagate forward at nearly the speed of light.

Because the electromagnetic waves inside a cable don't interact with those outside it, the transmitter and receiver can use whatever parts of the spectrum they choose, without concerns about sharing. A typical coaxial cable can handle frequencies up to about 1000 MHz and typical twisted-pair cable can reach 350 MHz, so either one can carry a great deal of information each second.

However, coaxial cables must now compete with optical fiber cables that guide light from one place to another. We'll examine optical fibers in Section 15.2. Like radio waves, light is an electromagnetic wave and can be amplitude or frequency modulated to represent information. However, light's frequency is extremely high; the frequencies of

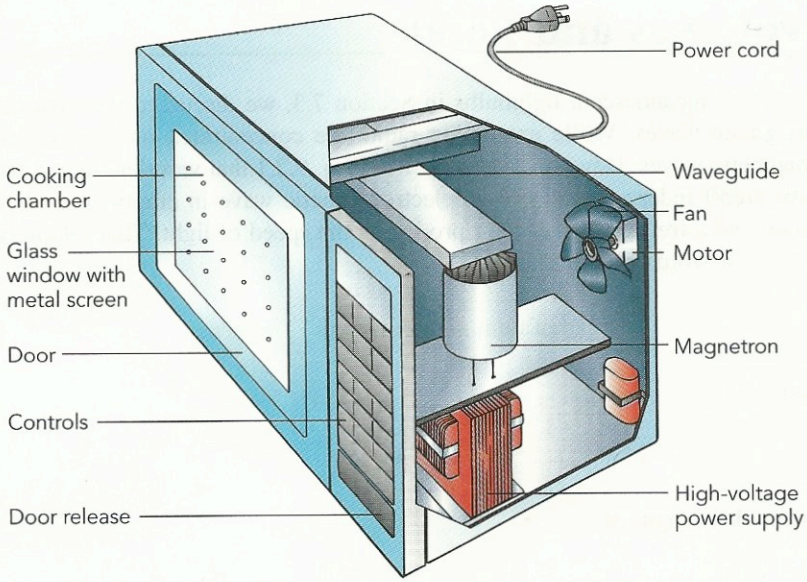
visible light range from 4.5×10^{14} Hz to 7.5×10^{14} Hz. If we were to allocate FM radio channels 200 kHz apart throughout the visible spectrum, there would be about 1.5 billion channels available!

Check Your Understanding #5: Beaten by the Bandwidth

You're playing piano for an AM radio station and you strike the highest key on the piano. The pitch of the resulting sound is 4186 Hz. Can the listeners hear that note from their radios?

Answer: Yes, they can hear it, at least in principle.

Why: The bandwidth of an AM radio station extends to 5000 Hz above and below its carrier frequency, so the station is officially permitted to represent sound frequencies as high as 5000 Hz. However, in practice the station probably begins to filter out sounds well below that frequency to avoid accidentally violating their license.



SECTION 13.2 Microwave Ovens

In addition to carrying sounds from one place to another, electromagnetic waves can carry power. One interesting example of such power transfer is a microwave oven. It uses relatively high-frequency electromagnetic waves to transfer power directly to the water molecules in food, so that the food cooks from the inside out. This section discusses both how those waves are created and why they heat food.

Questions to Think About: *Why do microwave ovens tend to cook food unevenly if you don't move the food during cooking? How can part of a frozen meal become boiling hot while another part remains frozen? Why must you be careful with metal objects placed inside the oven? Why do some objects remain cool in the microwave oven while other objects become extremely hot? How does microwave popcorn work?*

Experiments to Do: *A microwave oven transfers power primarily to the water in food. You can see this effect by placing completely water-free food ingredients such as salt, baking powder, sugar, or salad oil on a microwave-safe ceramic dish in a microwave oven. Cook the ingredients briefly. You will find that the ingredients and dish remain relatively cool. Add just a little water to the collection. What happens when you cook them this time?*

Now try cooking a very cold ice cube. The cube should come directly from the freezer on an ice-cold plate, so that its surface is solid and dry. What happens? If ice contains water and water is what absorbs power in a microwave oven, why doesn't the ice absorb power and melt?

Microwaves and Food

When studying incandescent lightbulbs in Section 7.3, we discussed the *wavelengths* of electromagnetic waves. While examining radio, we concentrated on the *frequencies* of electromagnetic waves. However, we know from Eq. 9.2.1 that wavelength and frequency of a wave aren't independent. A basic electromagnetic wave in empty space has both a wavelength and a frequency, and their product is the speed of light. That relationship can be written as a word equation:

$$\text{speed of light} = \text{wavelength} \cdot \text{frequency} \tag{13.2.1}$$

in symbols:

$$c = \lambda \cdot \nu,$$

and in everyday language:

The higher the frequency of an electromagnetic wave, the shorter its wavelength becomes.

Though he was orphaned as a child and never completed grade school, American Percy Lebaron Spencer (1894–1970) had a brilliant career as a scientist and microwave engineer. In 1945, while visiting a magnetron testing laboratory, he leaned over an operating magnetron and the candy bar in his shirt pocket melted. Immediately recognizing what had happened, he soon had popcorn popping about the lab and even cooked an egg until it exploded. Cooking has never been the same since.

Like Fig. 7.3.2, Fig. 13.2.1 shows the approximate wavelengths of many types of electromagnetic waves, but it also shows their frequencies.

Radio broadcasts use the low-frequency, long-wavelength portion of the electromagnetic spectrum. Commercial AM radio is at frequencies of 550 kHz to 1600 kHz (wavelengths of 545 m to 187 m) and commercial FM radio is at frequencies of 88 MHz to 108 MHz (wavelengths of 3.4 m to 2.8 m). Because these waves have wavelengths longer than 1 m, they are called radio waves. The electromagnetic waves used in microwave ovens have wavelengths shorter than 1 m and are called microwaves. **Microwaves** extend from wavelengths of 1 m (3.3 ft) down to 1 mm (0.04 in).

To explain how a microwave oven heats food, let's begin by looking at water molecules. Water molecules are electrically polarized—that is, they have positively charged ends and negatively charged ends. This polarization comes about because of quantum physics and the tendency of oxygen atoms to pull electrons away from hydrogen atoms. The water molecule is bent, with its two hydrogen atoms sticking up from its oxygen atom like Mickey Mouse's ears. When the oxygen atom pulls the electrons partly away

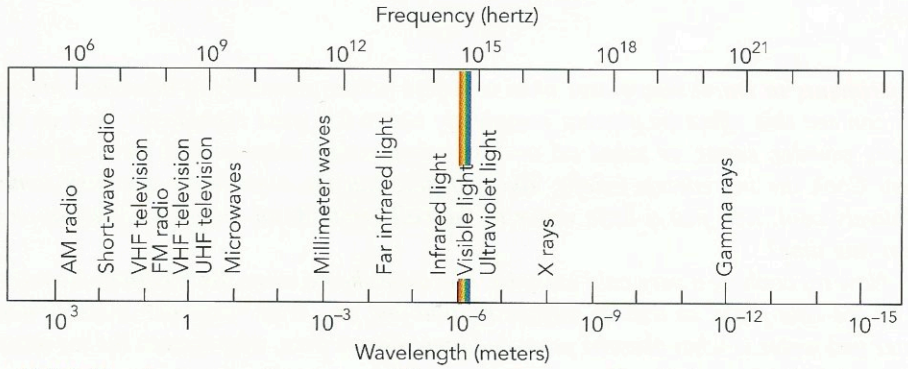


Fig. 13.2.1 The electromagnetic spectrum. Microwaves have wavelengths between about 1 m and 1 mm, corresponding to frequencies from 300 MHz up to 300 GHz.

from the hydrogen atoms, its side of the molecule becomes negatively charged while the hydrogen atoms' side becomes positively charged. Water is thus a polar molecule.

In ice, these polar water molecules are arranged in an orderly fashion with fixed positions and orientations. However, in liquid water, the molecules are more randomly oriented (Fig. 13.2.2). Their arrangements are constrained only by their tendency to bind together, positive end to negative end, to form a dense network of coupled molecules. This binding between the positively charged hydrogen atom on one water molecule and the negatively charged oxygen atom on another molecule is known as a *hydrogen bond.*

If you place liquid water in a strong electric field, its water molecules will tend to rotate into alignment with the field. That's because a misaligned molecule has extra electrostatic potential energy and accelerates in the direction that reduces its potential energy as quickly as possible. In this case, the water molecule will experience a torque and will undergo an angular acceleration that makes it rotate into alignment. As it rotates, the molecule will bump into other molecules and convert some of its electrostatic potential energy into thermal energy.

A similar effect occurs at a crowded party when everyone is suddenly told to face the front of the room. People brush against one another as they turn, and sliding friction converts some of their energy into thermal energy. If the people were told to turn back and forth repeatedly, they would become quite warm. The same holds true for water. If the electric field reverses its direction many times, the water molecules will turn back and forth and become hotter and hotter.

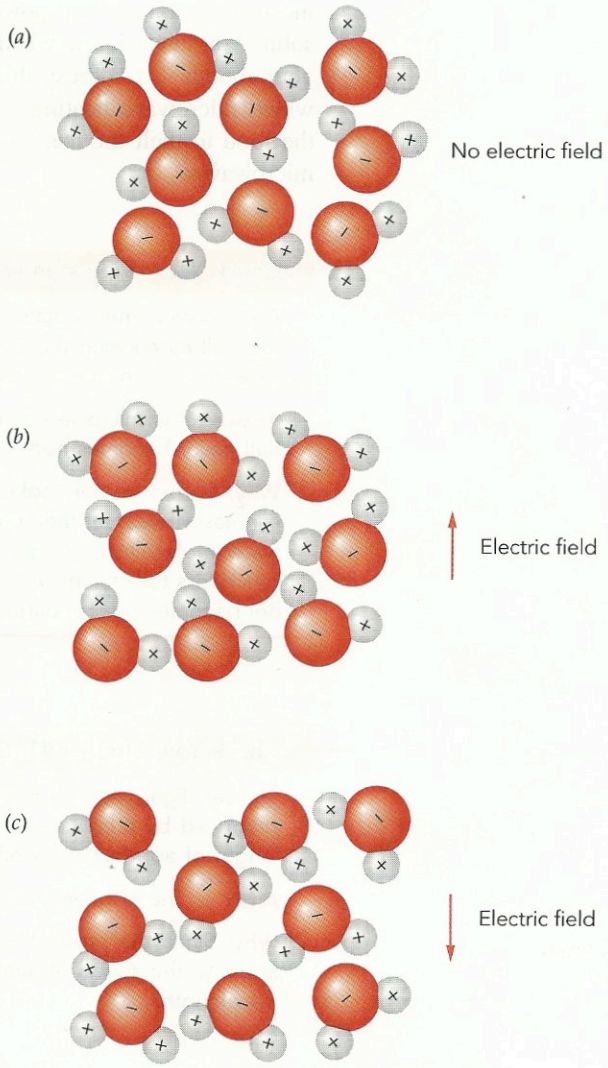


Fig. 13.2.2 (*a*) The water molecules in liquid water are randomly oriented when there's no electric field. (*b, c*) An electric field tends to orient them with their positive ends in the direction of the field.

A microwave's fluctuating electric field is well suited to heating water. A microwave oven uses 2.45-GHz (2.45-gigahertz or 2,450,000,000-Hz) microwaves to twist food's water molecules back and forth, billions of times per second. As the water molecules turn, they bump into one another and heat up. The water absorbs the microwaves and converts their energy into thermal energy. This particular microwave frequency was chosen not because of any resonant effect but because it was not in use for communications and because it cooks food uniformly. If the frequency were higher, the microwaves would be absorbed too strongly by food and wouldn't penetrate deep into large items. If the frequency were lower, the microwaves would pass through foods too easily and wouldn't cook efficiently.

This twisting effect explains why only foods or objects containing water or other polar molecules cook well in a microwave oven. Ceramic plates, glass cups, and plastic containers are water-free and usually remain cool. Even ice has trouble absorbing microwave power because its crystal structure constrains the water molecules so they can't turn easily.

Although ice melts slowly in a microwave oven, the liquid water it produces heats quickly. This peculiar heating behavior explains why it's so easy to burn yourself on frozen food heated in a microwave oven. Portions of the food that defrost first absorb

most of the microwave power and overheat, while the rest of the food remains frozen solid. You never know whether your next bite will break your teeth or sear the roof of your mouth. To address this problem, many microwave ovens have defrost cycles in which microwave heating is interrupted periodically to let heat flow naturally through the food to melt the ice. Once the frozen parts have melted, all of the food can absorb microwaves.

Check Your Understanding #1: **Microwave Popcorn**

A popcorn kernel contains moist starch trapped inside a hard, dry hull. You can scorch this hull by cooking the corn in hot oil but not when you cook it in a microwave oven. How can the microwave oven pop the corn without risk of overheating the hull?

Answer: The microwave oven transfers heat to water molecules in the starch so that the hull never becomes hotter than the material inside it.

Why: A corn kernel cooked in oil is heated by contact with the hot oil and pot. You can easily overheat the outer hull and burn it. However, microwaves transfer heat to the water molecules inside the kernel. The hull can't overheat, because the hottest thing it touches is the starchy insides of the kernel. When the pressure of steam inside the kernel becomes high enough, the hull breaks and the kernel "pops."

Check Your Figures #1: **Shopping for Food**

The red light used by many grocery store checkout stations to scan product codes is produced by a helium–neon laser. This light is an electromagnetic wave with a wavelength of approximately 633 nm. What is its frequency?

Answer: The frequency is about 4.74×10^{14} Hz.

Why: Since the product of frequency and wavelength for an electromagnetic wave is equal to the speed of light, its frequency is equal to the speed of light divided by its wavelength:

$$\frac{299{,}792{,}458\,\text{m/s}}{0.000000633\,\text{m}} = 4.74 \times 10^{14}\,\text{Hz}.$$

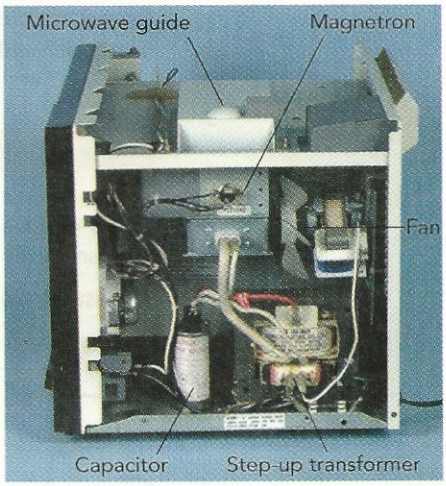
Metal in a Microwave Oven

Contrary to popular lore, metal objects and microwave ovens aren't always incompatible. In fact, the walls of the oven's cooking chamber are metal, yet they cause no trouble when exposed to microwaves during cooking. Like most metal surfaces, the walls reflect microwaves. They do this by acting as both receiving and transmitting antennas. Electric fields in the microwaves cause mobile charges in the metal surfaces to accelerate and absorb the original microwaves. As these charges accelerate, they emit new microwaves. The emitted microwaves have the same frequencies as the original ones, but they travel in new directions. The original microwaves have been reflected by the surface.

The cooking chamber walls reflect the oven's microwaves and keep them bouncing around inside. Even the metal grid covering the window reflects microwaves. That's because charge has enough time during a microwave cycle to flow around each hole in

the grid and compensate for the hole's presence. As long as the wavelength of an electromagnetic wave is much larger than the holes in a metal grid, the wave reflects perfectly from that grid. In fact, if there's nothing inside the oven to absorb the microwaves, they'll bounce around inside it until they return to their source, a vacuum tube called a magnetron (Fig. 13.2.3), and eventually cause it to overheat.

While metal surfaces help confine the microwaves inside the oven, cooking your food and not you, extra metal inside the microwave can cause trouble. If you wrap food in aluminum foil, the foil will reflect the microwaves and the food won't cook. However, food placed in a shallow metal dish cooks reasonably well because microwaves enter the open top, pass through the food, reflect, and pass through the food again.



Courtesy Lou Bloomfield

Fig. 13.2.3 This oven's magnetron microwave source is located in the middle of the picture, just to the left of its cooling fan. Microwaves travel to the cooking chamber through the rectangular metal duct on top of the oven. The high-voltage transformer at the bottom right provides power to the magnetron.

Sometimes metal's mobile charges do more than just reflect microwaves. If enough charge is pushed onto the sharp point of a metal twist-tie or scrap of aluminum foil, some of it will jump right into the air as a spark. This spark can start a fire, particularly when the twist-tie is attached to something flammable, like a plastic or paper bag. As a rule of thumb, never put a sharp metal object in the microwave oven.

Some metal objects heat up in a microwave oven. When microwaves push charge back and forth in a metal, the metal experiences an alternating current. If the metal has a substantial electrical resistance, this alternating current will experience a voltage drop and heat up the metal. While thick oven walls and cookware have low resistances and remain cool, thin metal strips quickly overheat. Metallic decorations on porcelain dinnerware are particularly susceptible to damage in a microwave oven, so that warming up coffee in Grandma's gold-rimmed teacup is sure disaster. When putting metal into a microwave oven, make sure that it is thick enough to conduct electricity well and that it has no sharp points.

Resistive heating in conducting objects can actually be useful at times. Since microwave ovens cook food inside and out at the same time, the food's surface never gets particularly hot and the food doesn't brown or become crisp. To improve their textures and appearances, some foods come with special wrappers that conduct just enough current to become very hot in a microwave oven. These wrappers provide the high surface temperatures needed to brown the foods.

Another peculiar feature of microwave ovens is that they don't always cook evenly. That's because the amplitude of the microwave electric field isn't uniform throughout the oven. As the microwaves bounce around the cooking chamber, they pass through the same spot from several different directions at once. When they do, they exhibit interference effects (see Section 9.3). At one location, the individual electric fields may point n the same direction and experience constructive interference, so that food there heats p quickly. At another location, however, those fields may point in opposite directions d experience destructive interference, so that food there doesn't cook well at all.

If nothing is moving in the microwave oven, the pattern of microwaves inside it n't move either. There are then regions in which the electric field has very large itudes and regions in which the amplitudes are very small. The larger the amplitude electric field, the faster it cooks food.

heat food uniformly in such a microwave oven, you must move the food around cooking. Many ovens have turntables inside that move the food automatically. solution to this problem is to stir the microwaves around the oven with a rotat- l paddle. The pattern of microwaves inside the chamber changes as the paddle l the food cooks more evenly. Still other microwave ovens use two separate

microwave frequencies to cook the food. Because these two frequencies cook independently, it's unlikely that a portion of the food will be missed by both waves at once.

Check Your Understanding #2: Half and Half

You place a thick metal divider into your microwave oven, so that it divides the cooking chamber exactly in half. The oven sends its microwaves into the right half of the chamber. If you put food in the left half of the chamber, will it cook?

Answer: No, it won't cook.

Why: The metal divider would reflect microwaves and keep them from entering the left half of the oven.

Creating Microwaves with a Magnetron

Clearly, changing electric fields cook the food as microwaves bounce around the inside of an oven. But how are these microwaves created? From the previous section on radio, you might guess that the oven creates an alternating current at 2.45 GHz and that this current causes charge to slosh in a tank circuit and move up and down an antenna. That's pretty much what actually happens inside a magnetron tube.

A magnetron is a special vacuum tube—a hollow chamber from which all the air has been removed. Composed primarily of metal and ceramic parts, the magnetron uses beams of electrons to make charge slosh in a number of microwave tank circuits. These tank circuits have resonant frequencies of 2.45 GHz, the operating frequency of the oven. With the help of a tiny antenna, the magnetron emits the microwaves that cook the food.

The microwave tank circuits are arranged in a ring around the magnetron's evacuated chamber. For one of these tank circuits to oscillate naturally at 2.45 GHz, its capacitor must have an extremely small capacitance and its inductor must have an extremely small inductance. These requirements can be met by a C-shaped strip of metal (Fig. 13.2.4). Its curve is the inductor and its tips are the capacitor.

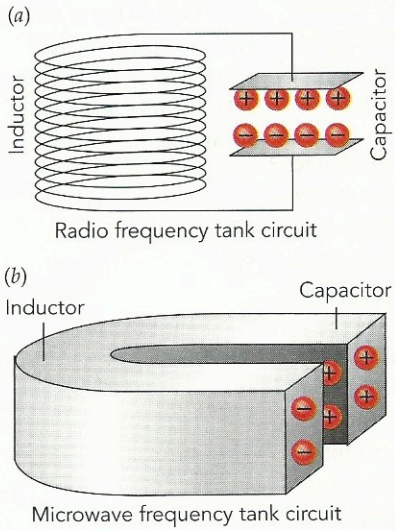


Fig. 13.2.4 (*a*) At radio frequencies, a tank circuit's inductor is a coil of wire, and its capacitor is a pair of separated plates. (*b*) At microwave frequencies, a tank circuit's inductor is merely the curve of a C-shaped strip, and its capacitor is the tips of that strip.

Electric charge sloshes back and forth on the C-shaped strip just as it does in a conventional tank circuit (Fig. 13.1.2). Known as a **resonant cavity**, this strip is another electronic harmonic oscillator and therefore has a period that doesn't depend on the amount of charge that's sloshing.

The magnetron of a microwave oven typically contains eight of these resonant cavities, each carefully adjusted in size and shape so that its natu ral resonance occurs exactly at 2.45 GHz. Because these cavities ar arranged in a ring and each one shares its tips with those of its neighboring cavities, th tend to oscillate alternately (Fig. 13.2.5). At the start of an oscillatory cycle, half metal tips are positively charged and half are negatively charged (Fig. 13.2.5*a*). Cur begin to flow through the ring and produce magnetic fields in the resonant ca (Fig. 13.2.5*b*). These magnetic fields propel the currents around the ring even af charge separations have vanished. Soon the charge separations reappear but with t itive and negative tips interchanged (Fig. 13.2.5*c*).

These currents oscillate back and forth around the cavities at 2.45 GHz, f magnetron with alternating electric and magnetic fields. However, as the energy fields is extracted to cook the food or is lost to the imperfect conductivities of th

themselves, something must continuously replenish it. That replacement power is supplied to the cavities by four streams of energetic electrons.

At the center of the magnetron tube, surrounded only by empty space, is an electrically heated cathode that tends to emit electrons (Fig. 13.2.6*a*). A high-voltage power supply pumps negative charge onto this cathode so that a strong electric field points toward it from the positively charged cavity tips. If there were no other fields present in the magnetron, negatively charged electrons would emerge from the hot cathode and accelerate toward the positively charged tips as four beams of electrons (Fig. 13.2.6*b*).

However, the magnetron also includes a large permanent magnet. Why else would it be called a magnetron? This magnet creates a strong, steady magnetic field that points upward along the axis of the magnetron, parallel to the cathode itself (Fig. 13.2.6*c*). If there were no other fields inside the magnetron, electrons would experience only Lorentz forces perpendicular to their velocities and would circle around the magnetic flux lines in counterclockwise loops—a behavior known as **cyclotron motion**. The circling electrons would remain near the cathode and would never go near the cavities.

In a real magnetron, however, the electric field of Fig. 13.2.6*b* and the magnetic field of Fig. 13.2.6*c* are present simultaneously. Because both of these fields exert forces on moving electrons, the paths the electrons follow are extremely complicated (Fig. 13.2.6*d*). The outward-directed and circulating motions merge together into four electron beams that arc outward and rotate counterclockwise, like the spokes of a spinning bicycle wheel. An electron beam reaches each cavity not at its positively charge tip, as it would without the magnetic field, but at its negatively charged tip. The electron beams actually add to the charge separations in the cavities!

The electron beams sweep around the cathode in perfect synchronization with the oscillating charge on the cavities. The beams sweep from one tip to the next in the same

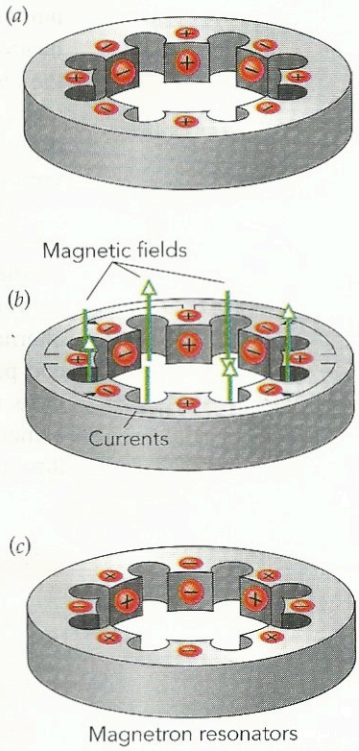
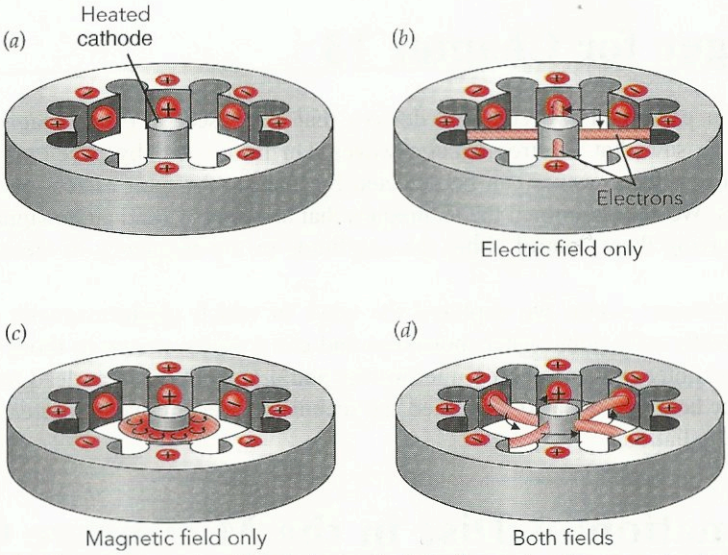


Fig. 13.2.5 A typical magnetron has eight C-shaped resonant cavities arranged in a ring. (*a*) Separated charge on the tips of the cavities (*b*) flows as currents through the ring and (*c*) becomes reversed. As the currents flow, magnetic fields appear in the eight cavities, pointing alternately up and down.



?.6 (*a*) Electrons are emitted by the hot cathode in the center of a magnetron's ring of cavities. (*b*) Electric fields alone would accelerate the electrons toward the positively avity tips. (*c*) A magnetic field alone (pointing upward) would make the electrons orbit e in counterclockwise loops. (*d*) Together, these fields create spokelike electron beams the cathode counterclockwise and always strike negatively charged tips of the cavities.

amount of time it takes for the charge separation on the tips to reverse. As a result, the beams always arrive on the negatively charged tip. By adding to the charge separations, the electron beams provide power to the oscillations in the cavities, keeping them going and allowing them to transfer power to the food. The electron beams actually initiate the oscillation in the cavities by adding energy to tiny random oscillations that are always present in electric systems.

How does the oscillating charge inside the magnetron create microwaves inside the oven's cooking chamber? There are many ways to extract microwaves from the ring of cavities. One extraction method is to insert a single-turn wire coil into one of the magnetron's cavities. As the magnetic field in that cavity changes, it induces a 2.45-GHz alternating current in the coil. One end of this coil is attached to the ring, but the other end passes out of the magnetron through an insulated, airtight hole in the ring and connects to a quarter-wavelength antenna. This 3-cm (1.2-in) antenna emits microwaves into a metal pipe attached to the cooking chamber. These microwaves reflect their way through the pipe and into the cooking chamber, where they cook the food.

Check Your Understanding #3: Large Economy Size

If a manufacturer made a magnetron that was slightly larger than normal in every dimension, how would that magnetron behave?

Answer: It would operate at a frequency below 2.45 GHz.

Why: The frequency of the microwaves emitted by a magnetron is determined exclusively by the natural resonances of its cavities. If those cavities are enlarged, both the inductances of their curves and the capacitances of their tips will increase. Their resonant frequencies will decrease, and the magnetron will emit lower frequency microwaves.

Epilogue for Chapter 13

This chapter examined two common devices that are based on electromagnetic waves. In *radio*, we saw that electromagnetic waves can be created by accelerating electric charge and that these waves can be detected by looking for their effects on other electric charges. We also examined the techniques that are used to send audio signals through space by having them control either the amplitude or the frequency of electromagnetic waves.

In *microwave ovens*, we explored the ways in which electromagnetic waves ca interact directly with polar water molecules and can transfer energy to those molecul We saw how interactions between microwaves and a metal object can lead to reflect sparking, or heating. We also examined the technique used in ovens to create powe microwave radiation.

Explanation: A Disc in the Microwave Ov

The fluctuating electric field in the microwave oven propels large currents back a through the disc's metal layer. That layer is so thin that it has a large electric resist it heats up as the current flows through it. The temperature of the plastic also rise of its intimate contact with the metal layer. Since the plastic has a larger coe

volume expansion than the metal, the expanding plastic tears the metal layer and reduces it to islands with sharp points and narrow bridges.

Once the metal layer has fragmented, the microwave-driven currents can put substantial electric charges on the sharp points. Those charges can jump between islands as sparks. The currents passing through narrow conducting bridges can heat those bridges so hot that their metal vaporizes and they form glowing, current-carrying plasma arcs.

Chapter Summary

How Radio Works: A radio transmitter creates a radio wave when electric charge accelerates up and down its antenna. To get as much charge moving as possible, the transmitter attaches a tank circuit to the antenna and slowly adds energy to that tank circuit until an enormous amount of charge is flowing up and down the antenna. If the antenna is a quarter-wavelength long, it's also resonant at the transmission frequency and boosts the amount of charge sloshing up and down.

The radio receiver detects this radio wave when it causes charge to accelerate up and down the receiving antenna. If both the receiving antenna and the receiver's tank circuit are resonant at the transmission frequency, large amounts of charge will slosh back and forth in the receiver's tank circuit, and the receiver will detect the transmission.

This radio wave can represent sound using either the AM or FM technique. In the AM technique, the strength of the wave is increased or decreased to represent compressions and rarefactions of the air, respectively. In the FM technique, the precise frequency of the transmission is increased or decreased to represent those compressions or rarefactions.

How Microwave Ovens Work: A microwave oven uses microwaves to cook food. These microwaves bounce around the cooking chamber, where they transfer energy to water molecules in the food. Because a water molecule is polar, having a positive end and a negative end, it tends to align with an electric field. The microwave's fluctuating electric field causes the tightly packed water molecules to twist back and forth rapidly, and the ensuing collisions heat the water and cook the food.

The oven's microwaves are produced by a magnetron, a vacuum tube containing resonant cavities and a heated cathode. By combining strong electric and magnetic fields, the magnetron produces powerful beams of electrons that add energy to the charge oscillating in the cavities. A loop of wire and a short antenna extract power from the resonant cavities and emit the microwaves that then cook the food.

Important Laws and Equations

1. The Energy in an Electric Field: The energy of an electric field is equal to the square of that field times its volume, divided by 8π times the Coulomb constant, or

$$\text{energy} = \frac{\text{electric field}^2 \cdot \text{volume}}{8\pi \cdot \text{Coulomb constant}}. \qquad (13.1.1)$$

2. Relationship between Wavelength and Frequency: The product of the frequency of an electromagnetic wave times its wavelength is the speed of light, or

$$\text{speed of light} = \text{wavelength} \cdot \text{frequency}. \qquad (13.2.1)$$

Exercises

1. If you pull a permanent magnet rapidly away from a tank circuit, what is likely to happen in that circuit?

2. Will the speed with which you pull the magnet away from the tank circuit (Exercise 1) affect the period of its charge oscillation?

3. A tank circuit consists of an inductor and a capacitor. Give a simple explanation for why the magnetic field in the inductor is strongest at the moment the separated charge in the capacitor reaches zero.

4. The metal wires from which most tank circuits are made have electrical resistances. Why do these resistances prevent charge from oscillating forever in a tank circuit, and what happens to the tank circuit's energy as time passes?

5. To add energy to the charge oscillation in a tank circuit with an antenna, at which time during the oscillation cycle should you bring a positively charged wand close to the antenna?

6. Two identical tank circuits with antennae are next to one another. Explain why charge oscillating in one tank circuit can continue to do work on charge oscillating in the other tank circuit.

7. The ignition system of an automobile produces sparks to ignite the fuel in the engine. During each spark process, charges suddenly accelerate through a spark plug wire and across a spark plug's narrow gap. Sometimes this process introduces noise into your radio reception. Why?

8. To diminish the radio noise in a car (see Exercise 7), the ignition system uses wires that are poor conductors of electricity. These wires prevent charges from accelerating rapidly. Why does this change improve your radio reception?

9. The electronic components inside a computer transfer charge to and from wires, often in synchrony with the computer's internal clock. Without packaging to block electromagnetic waves, the computer will act as a radio transmitter. Why?

10. To save power in a computer, its thousands of wires usually avoid sharp bends. Why do sharp bends in current-carrying wires waste power?

11. The sun emits a stream of energetic electrons and protons called the solar wind. These particles frequently get caught up in the earth's magnetic field, traveling in spiral paths that take them toward the north or south magnetic poles. When they head northward and collide with atoms in the earth's upper atmosphere, those atoms emit light we know as the aurora borealis, or northern lights. These particles also interfere with radio reception. Why do they emit radio waves?

12. When a radio signal travels through a coaxial cable, charge moves back and forth on both the central wire and the surrounding tube. Show that both electric and magnetic fields are present in the coaxial cable.

13. If you wave a positively charged wand up and down vertically, the electromagnetic wave it emits has which polarization?

14. If you set a magnetic compass on the table and spin its magnetic needle horizontally, its accelerating poles will emit an electromagnetic wave with which polarization?

15. Although a particular AM radio station claims to transmit 50,000 W of music power, that's actually its average power. There are times when it transmits more power than that and times when it transmits less. Explain.

16. When your receiver is too far from an AM radio station, you can only hear the loud parts of the transmission. When it's too far from an FM station, you lose the whole sound all at once. Explain the reasons for this difference.

17. When an AM radio station announces that it's transmitting at 950 kHz, that statement isn't quite accurate. Explain why it may also be transmitting at 948 kHz and 954 kHz.

18. The Empire State Building has several FM antennas on top, added in part to increase its overall height. These antennas aren't very tall. Why do short antennas, located high in the air, do such a good job of transmitting FM radio?

19. Porous, unglazed ceramics can absorb water and moisture. Why are they unsuitable for use in a microwave oven?

20. Why are most microwave TV dinners packaged in plastic rather than aluminum trays?

21. Why is it so important that a microwave oven turn off when you open the door?

22. Compare how a potato cooks in a microwave oven with how it cooks in an ordinary oven.

23. When you're listening to FM radio near buildings, reflections of the radio wave can make the reception particularly bad in certain locations. Compare this effect to the problem of uneven cooking in a microwave oven.