EXAMPLE 22–7 **Tuning a station.** Calculate the transmitting wavelength of an FM radio station that transmits at 100.1 MHz.

APPROACH Radio is transmitted as an EM wave, so the speed is $c = 3.0 \times 10^8\,\mathrm{m/s}$. The wavelength is found from Eq. 22–4, $\lambda = c/f$.

SOLUTION The carrier frequency is $f = 100.1\,\mathrm{MHz} \approx 1.0 \times 10^8\,\mathrm{s^{-1}}$, so

$$\lambda = \frac{c}{f} = \frac{(3.0 \times 10^8\,\mathrm{m/s})}{(1.0 \times 10^8\,\mathrm{s^{-1}})} = 3.0\,\mathrm{m}.$$

NOTE The wavelengths of other FM signals (88 MHz to 108 MHz) are close to the 3.0-m wavelength of this station. FM antennas are typically 1.5 m long, or about a half wavelength. This length is chosen so that the antenna reacts in a resonant fashion and thus is more sensitive to FM frequencies. AM radio antennas would have to be very long and impractical to be either $\frac{1}{2}\lambda$ or $\frac{1}{4}\lambda$.

Other EM Wave Communications

PHYSICS APPLIED
Cell phones, remote controls, cable TV, satellite TV and radio

The various regions of the radio-wave spectrum are assigned by governmental agencies for various purposes. Besides those mentioned above, there are "bands" assigned for use by ships, airplanes, police, military, amateurs, satellites and space, and radar. Cell phones, for example, are complete radio transmitters and receivers. In the U.S., CDMA cell phones function on two different bands: 800 MHz and 1900 MHz (= 1.9 GHz). Europe, Asia, and much of the rest of the world use a different system: the international standard called GSM (Global System for Mobile Communication), on 900-MHz and 1800-MHz bands. The U.S. now also has the GSM option (at 850 MHz and 1.9 GHz), as does much of the rest of the Americas. A 700-MHz band is being made available for cell phones (it used to carry TV broadcast channels, no longer used). Radio-controlled toys (cars, sailboats, robotic animals, etc.) can use various frequencies from 27 MHz to 75 MHz. Automobile remote entry (keyless) may operate around 300 MHz or 400 MHz.

Cable TV channels are carried as electromagnetic waves along a coaxial cable (Fig. 22–9) rather than being broadcast and received through the "air." The channels are in the same part of the EM spectrum, hundreds of MHz, but some are at frequencies not available for TV broadcast. Digital satellite TV and radio are carried in the microwave portion of the spectrum (12 to 14 GHz and 2.3 GHz, respectively).

Wireless from the Moon

In 1969, astronauts first landed on the Moon. It was shown live on television (Fig. 22–20). The transmitting TV camera can be seen in the Chapter-Opening photo, page 625. At that time, someone pointed out that Columbus and other early navigators could have imagined that humans might one day reach the Moon. But they would never have believed possible that moving images could be sent from the Moon to the Earth through empty space.

FIGURE 22–20 The first person on the Moon, Neil Armstrong, July 20, 1969, pointed out "One small step for a man, one giant leap for mankind."

Summary

James Clerk Maxwell synthesized an elegant theory in which all electric and magnetic phenomena could be described using four equations, now called **Maxwell's equations**. They are based on earlier ideas, but Maxwell added one more—that a changing electric field produces a magnetic field.

Maxwell's theory predicted that transverse **electromagnetic (EM) waves** would be produced by accelerating electric charges, and these waves would propagate (move) through space at the speed of light:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8\,\mathrm{m/s}. \qquad \textbf{(22–3)}$$

The oscillating electric and magnetic fields in an EM wave are perpendicular to each other and to the direction of propagation. These EM waves are waves of fields, not matter, and can propagate in empty space.

The wavelength λ and frequency f of EM waves are related to their speed c by

$$c = \lambda f \qquad \textbf{(22–4)}$$

just as for other waves.

After EM waves were experimentally detected, it became generally accepted that light is an EM wave. The **electromagnetic spectrum** includes EM waves of a wide variety of wavelengths, from microwaves and radio waves to visible light to X-rays and gamma rays, all of which travel through space at a speed $c = 3.0 \times 10^8$ m/s.

The average *intensity* $(\mathrm{W/m^2})$ of an EM wave is

$$\bar{I} = \frac{1}{2}\epsilon_0 c E_0^2 = \frac{1}{2}\frac{c}{\mu_0}B_0^2 = \frac{1}{2}\frac{E_0 B_0}{\mu_0}, \qquad \textbf{(22–8)}$$

where E_0 and B_0 are the peak values of the electric and magnetic fields, respectively, in the wave.

EM waves carry momentum and exert a **radiation pressure** proportional to the intensity I of the wave.

Radio, TV, cell phone, and other wireless signals are transmitted through space in the radio-wave or microwave part of the EM spectrum.

Questions

1. The electric field in an EM wave traveling north oscillates in an east–west plane. Describe the direction of the magnetic field vector in this wave. Explain.
2. Is sound an EM wave? If not, what kind of wave is it?
3. Can EM waves travel through a perfect vacuum? Can sound waves?
4. When you flip a light switch on, does the light go on immediately? Explain.
5. Are the wavelengths of radio and television signals longer or shorter than those detectable by the human eye?
6. When you connect two loudspeakers to the output of a stereo amplifier, should you be sure the lead-in wires are equal in length to avoid a time lag between speakers? Explain.
7. In the electromagnetic spectrum, what type of EM wave would have a wavelength of 10^3 km? 1 km? 1 m? 1 cm? 1 mm? 1 μm?
8. Can radio waves have the same frequencies as sound waves (20 Hz–20,000 Hz)?
9. If a radio transmitter has a vertical antenna, should a receiver's antenna (rod type) be vertical or horizontal to obtain best reception?
10. The carrier frequencies of FM broadcasts are much higher than for AM broadcasts. On the basis of what you learned about diffraction in Chapter 11, explain why AM signals can be detected more readily than FM signals behind low hills or buildings.
11. Discuss how cordless telephones make use of EM waves. What about cell phones?
12. A lost person may signal by switching a flashlight on and off using Morse code. This is actually a modulated EM wave. Is it AM or FM? What is the frequency of the carrier, approximately?

MisConceptual Questions

1. In a vacuum, what is the difference between a radio wave and an X-ray?
   (*a*) Wavelength. (*b*) Frequency. (*c*) Speed.
2. The radius of an atom is on the order of 10^{-10} m. In comparison, the wavelength of visible light is
   (*a*) much smaller. (*b*) about the same size. (*c*) much larger.
3. Which of the following travel at the same speed as light? (Choose all that apply.)
   (*a*) Radio waves. (*d*) Ultrasonic waves. (*g*) Gamma rays.
   (*b*) Microwaves. (*e*) Infrared radiation. (*h*) X-rays.
   (*c*) Radar. (*f*) Cell phone signals.
4. Which of the following types of electromagnetic radiation travels the fastest?
   (*a*) Radio waves.
   (*b*) Visible light waves.
   (*c*) X-rays.
   (*d*) Gamma rays.
   (*e*) All the above travel at the same speed.
5. In empty space, which quantity is always larger for X-ray radiation than for a radio wave?
   (*a*) Amplitude. (*c*) Frequency.
   (*b*) Wavelength. (*d*) Speed.
6. If electrons in a wire vibrate up and down 1000 times per second, they will create an electromagnetic wave having
   (*a*) a wavelength of 1000 m. (*c*) a speed of 1000 m/s.
   (*b*) a frequency of 1000 Hz. (*d*) an amplitude of 1000 m.
7. If the Earth–Sun distance were doubled, the intensity of radiation from the Sun that reaches the Earth's surface would
   (*a*) quadruple. (*b*) double. (*c*) drop to $\frac{1}{2}$. (*d*) drop to $\frac{1}{4}$.
8. An electromagnetic wave is traveling straight down toward the center of the Earth. At a certain moment in time the electric field points west. In which direction does the magnetic field point at this moment?
   (*a*) North. (*d*) West. (*g*) Either (*a*) or (*b*).
   (*b*) South. (*e*) Up. (*h*) Either (*c*) or (*d*).
   (*c*) East. (*f*) Down. (*i*) Either (*e*) or (*f*).
9. If the intensity of an electromagnetic wave doubles,
   (*a*) the electric field must also double.
   (*b*) the magnetic field must also double.
   (*c*) both the magnetic field and the electric field must increase by a factor of $\sqrt{2}$.
   (*d*) Any of the above.
10. If all else is the same, for which surface would the radiation pressure from light be the greatest?
    (*a*) A black surface.
    (*b*) A gray surface.
    (*c*) A yellow surface.
    (*d*) A white surface.
    (*e*) All experience the same radiation pressure, because they are exposed to the same light.
11. Starting in 2009, TV stations in the U.S. switched to digital signals. [See Sections 22–7, 17–10, and 17–11.] To watch today's digital broadcast TV, could you use a pre-2009 TV antenna meant for analog? Explain.
    (*a*) No; analog antennas do not receive digital signals.
    (*b*) No; digital signals are broadcast at different frequencies, so you need a different antenna.
    (*c*) Yes; digital signals are broadcast with the same carrier frequencies, so your old antenna will be fine.
    (*d*) No; you cannot receive digital signals through an antenna and need to switch to cable or satellite.