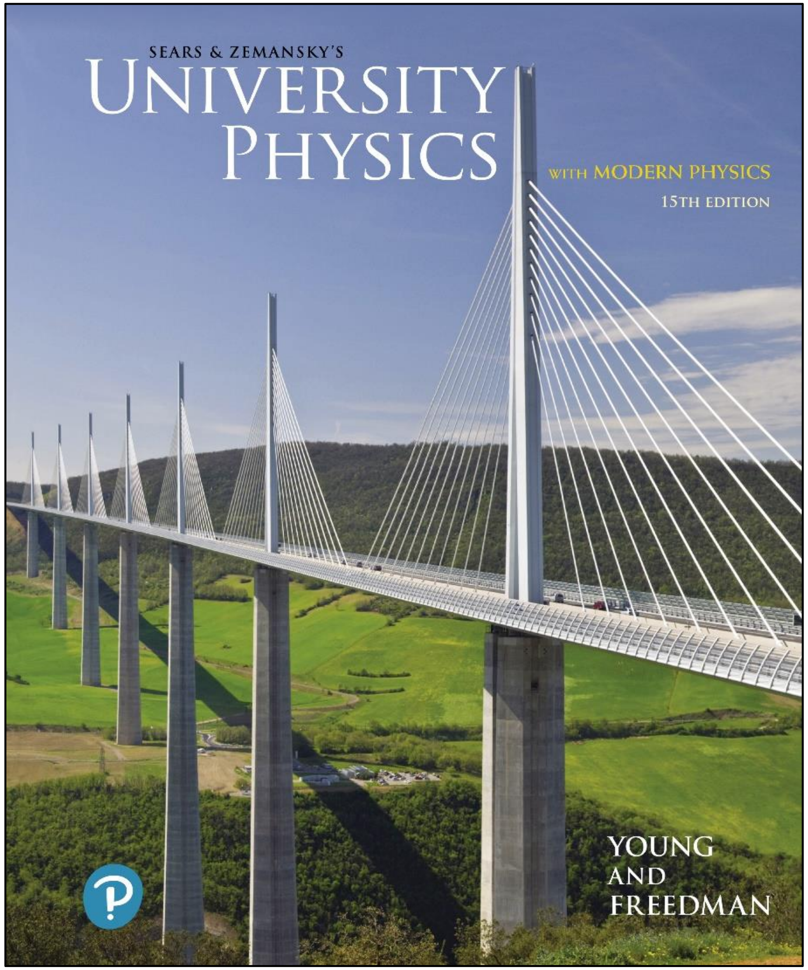
University Physics with Modern Physics

Fifteenth Edition



Chapter 32

Electromagnetic Waves

Pearson

Ultraviolet Vision

- Many insects and birds can see ultraviolet wavelengths that humans cannot.
- As an example, the left-hand photo shows how black-eyed Susans look to us.

- The right-hand photo (in false color), taken with an ultraviolet-sensitive camera, shows how these same flowers appear to the bees that pollinate them.
- Note the prominent central spot that is invisible to humans.

Pearson

Learning Outcomes

In this chapter, you'll learn…

- how electromagnetic waves are generated.
- how and why the speed of light is related to the fundamental constants of electricity and magnetism.
- how to describe the propagation of a sinusoidal electromagnetic wave.
- what determines the amount of energy and momentum carried by an electromagnetic wave.
- how to describe standing electromagnetic waves.

Pearson

Introduction

- Why do metals reflect light?
- We will see that light is an electromagnetic wave.
- There are many other examples of electromagnetic waves, such as radiowaves and x rays.

- Unlike sound or waves on a string, these waves do not require a medium to travel.

Pearson

James Clerk Maxwell and Electromagnetic Waves

- The Scottish physicist James Clerk Maxwell (1831–1879) was the first person to truly understand the fundamental nature of light.
- He proved in 1865 that an electromagnetic disturbance should propagate in free space with a speed equal to that of light.
- From this, he deduced correctly that light was an electromagnetic wave.

Pearson

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{encl}}{\epsilon_0} \qquad \text{(Gauss's law)} \qquad (29.18)$$

$$\oint \vec{B} \cdot d\vec{A} = 0 \qquad \text{(Gauss's law for magnetism)} \qquad (29.19)$$

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \qquad \text{(Faraday's law)} \qquad (29.20)$$

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \left(i_C + \epsilon_0 \frac{d\Phi_E}{dt} \right)_{encl} \qquad \text{(Ampere's law)} \qquad (29.21)$$

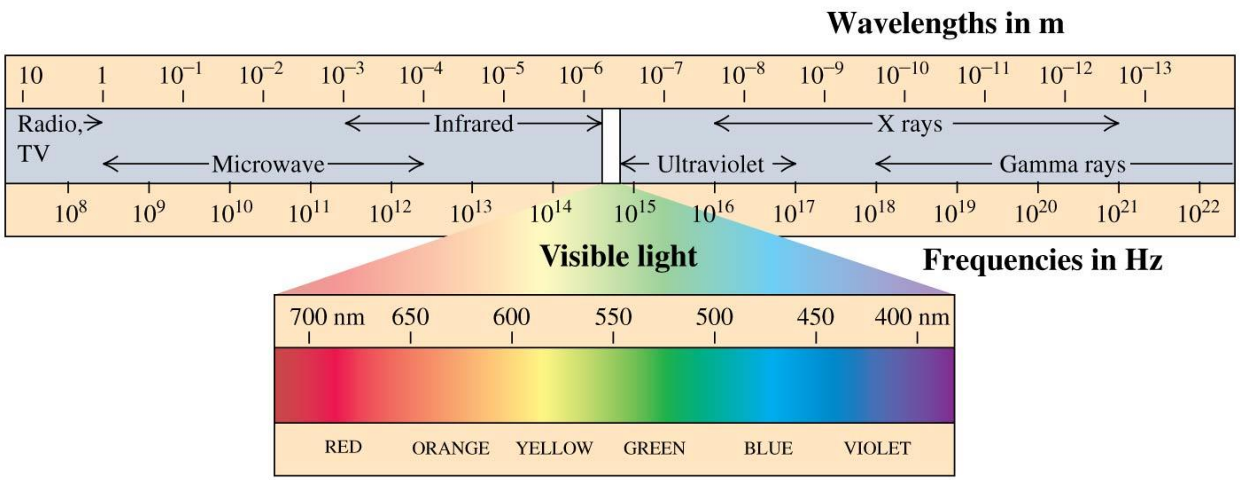
Electricity, Magnetism, and Light

- According to Maxwell’s equations, an accelerating electric charge must produce electromagnetic waves.
- For example, power lines carry a strong alternating current, which means that a substantial amount of charge is accelerating back and forth and generating electromagnetic waves.
- These waves can produce a buzzing sound from your car radio when you drive near the lines.

(b)

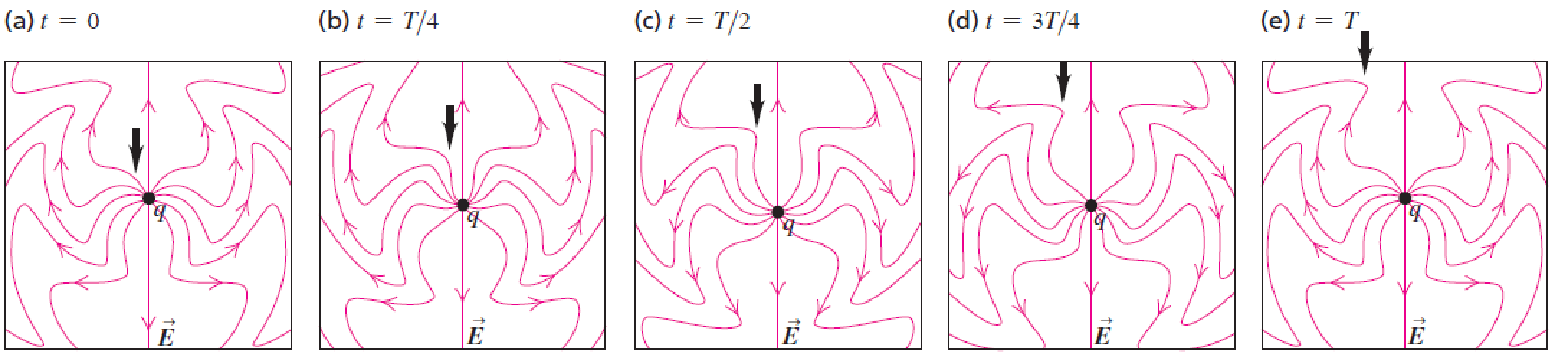
The Electromagnetic Spectrum

- The frequencies and wavelengths of electromagnetic waves found in nature extend over such a wide range that we have to use a logarithmic scale to show all important bands.
- The boundaries between bands are somewhat arbitrary.

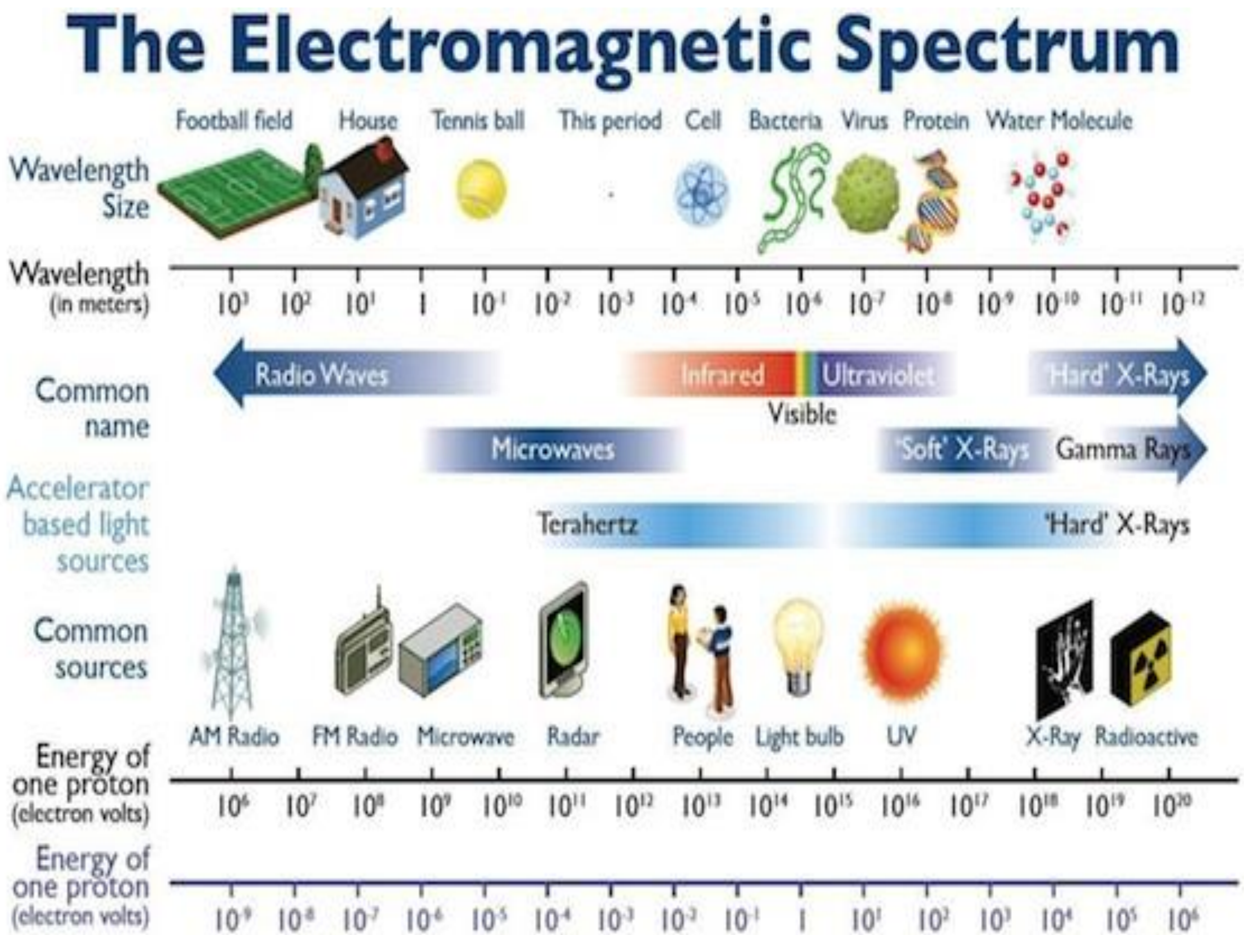


Pearson

Figure 32.3 Electric field lines of a point charge oscillating in simple harmonic motion, seen at five instants during an oscillation period T. The charge's trajectory is in the plane of the drawings. At $t = 0$ the point charge is at its maximum upward displacement. The arrow shows one "kink" in the lines of $\vec{E}$ as it propagates outward from the point charge. The magnetic field (not shown) contains circles that lie in planes perpendicular to these figures and concentric with the axis of oscillation.



$$c = 299{,}792{,}458 \text{ m/s.}$$


The Electromagnetic Spectrum
Football field
House
Tennis ball
This period
Cell
Bacteria
Virus
Protein
Water Molecule
Wavelength Size
Wavelength (in meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
Common name
Radio Waves
Infrared
Ultraviolet
'Hard' X-Rays
Visible
Microwaves
'Soft' X-Rays
Gamma Rays
Accelerator based light sources
Terahertz
'Hard' X-Rays
Common sources
AM Radio
FM Radio
Microwave
Radar
People
Light bulb
UV
X-Ray
Radioactive
Energy of one proton (electron volts)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy of one proton (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Visible Light

- **Visible light** is the segment of the electromagnetic spectrum that we can see.
- Visible light extends from the violet end (400 nm) to the red end (700 nm).

Table 32.1 Wavelengths of Visible Light

380–450 nm	Violet
450–495 nm	Blue
495–570 nm	Green
570–590 nm	Yellow
590–620 nm	Orange
620–750 nm	Red

Invisible forms of electromagnetic radiation are no less important than visible light. Our system of global communication, for example, depends on radio waves: AM radio uses waves with frequencies from 5.4×10^5 Hz to 1.6×10^6 Hz, and FM radio broadcasts are at frequencies from 8.8×10^7 Hz to 1.08×10^8 Hz. Microwaves are also used for communication (for example, by mobile phones and wireless networks) and for weather radar (at frequencies near 3×10^9 Hz).

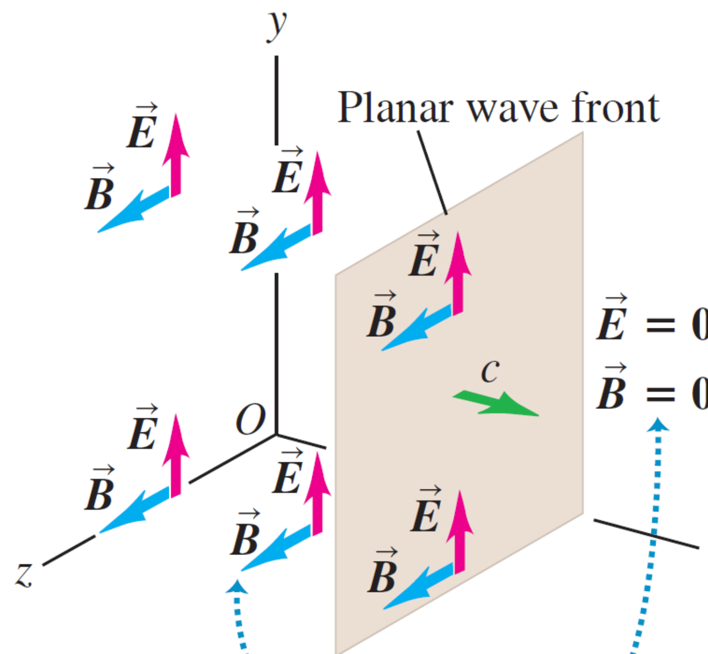
TEST YOUR UNDERSTANDING OF SECTION 32.1 (a) Is it possible to have a purely electric wave propagate through empty space—that is, a wave made up of an electric field but no magnetic field? (b) What about a purely magnetic wave, with a magnetic field but no electric field?

(a) **no,** (b) **no** A purely electric wave would have a varying electric field. Such a field necessarily generates a magnetic field through Ampere's law, Eq. (29.21), so a purely electric wave is impossible. In the same way, a purely magnetic wave is impossible: The varying magnetic field in such a wave would automatically give rise to an electric field through Faraday's law, Eq. (29.20).

ANSWER

A Simple Plane Electromagnetic Wave

- To begin our study of electromagnetic waves, imagine that all space is divided into two regions by a plane perpendicular to the *x*-axis.
- At every point to the left of this plane there are uniform electric field magnetic fields as shown.
- The boundary plane, which we call the **wave front**, moves in the +*x*-direction with a constant speed *c*.



The electric and magnetic fields are uniform behind the advancing wave front and zero in front of it.

A Simple Plane Electromagnetic Wave

Figure 32.5 An electromagnetic wave front. The plane representing the wave front moves to the right (in the positive x-direction) with speed c.

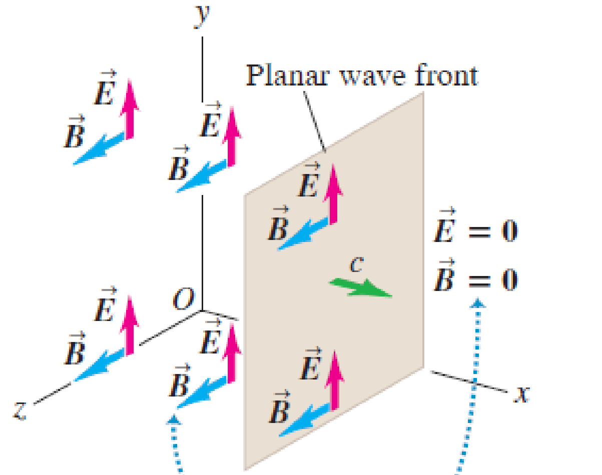
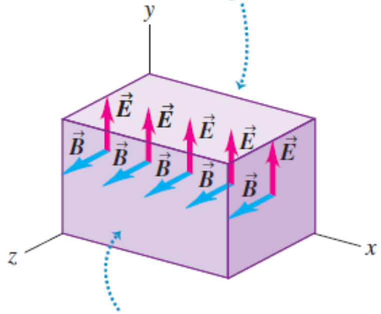


Figure 32.6 Gaussian surface for a transverse plane electromagnetic wave.



$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$$

$$\oint \vec{E} \cdot d\vec{l} = -Ea$$

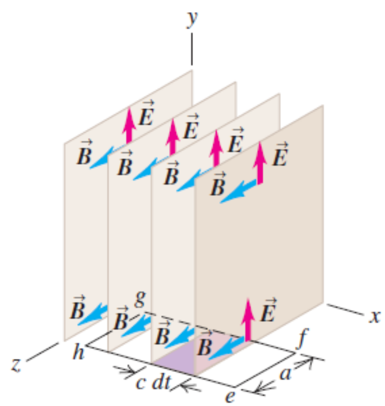
$$d\Phi_B = B(ac\,dt), \qquad \frac{d\Phi_B}{dt} = Bac$$

Electromagnetic wave in vacuum: $$E = cB \quad (32.4)$$

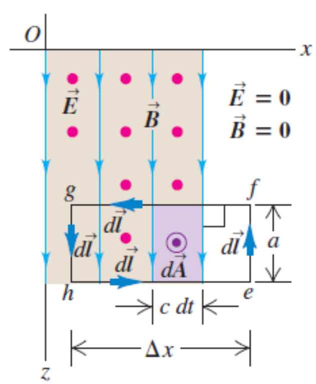
(Electric-field magnitude: E; Magnetic-field magnitude: B; Speed of light in vacuum: c)

Figure 32.8 (a) Applying Ampere's law to a plane wave. (Compare to Fig. 32.7a.) (b) In a time dt, the electric flux through the rectangle in the xz-plane increases by an amount $d\Phi_E$. This increase equals the flux through the shaded rectangle with area $ac\,dt$; that is, $d\Phi_E = Eac\,dt$. Thus $d\Phi_E/dt = Eac$.

(a) In time dt, the wave front moves a distance $c\,dt$ in the $+x$-direction.



(b) Top view of situation in (a)



$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

$$\oint \vec{B} \cdot d\vec{l} = Ba$$

$$d\Phi_E = E(ac\,dt).$$

$$\frac{d\Phi_E}{dt} = Eac$$

Electromagnetic wave in vacuum:

$$B = \epsilon_0 \mu_0 c E \qquad (32.8)$$

Magnetic-field magnitude (B); Electric-field magnitude (E); Electric constant (ϵ_0); Magnetic constant (μ_0); Speed of light in vacuum (c)

Pearson

Speech of electromagnetic waves in vacuum

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \tag{32.9}$$

Electric constant (ϵ_0)

Magnetic constant (μ_0)

Inserting the numerical values of these quantities to four significant figures, we find

$$c = \frac{1}{\sqrt{(8.854 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2})(1.257 \times 10^{-6}\ \mathrm{N/A^2})}}$$

$$= 2.998 \times 10^{8}\ \mathrm{m/s}$$

Pearson

Key Properties of Electromagnetic Waves

We chose a simple wave for our study in order to avoid mathematical complications, but this special case illustrates several important features of *all* electromagnetic waves:

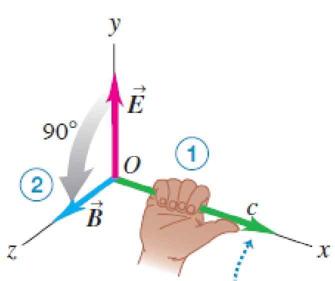
1. The wave is *transverse;* both $\vec{E}$ and $\vec{B}$ are perpendicular to the direction of propagation of the wave. The electric and magnetic fields are also perpendicular to each other. The direction of propagation is the direction of the vector product $\vec{E} \times \vec{B}$ (**Fig. 32.9**).
2. There is a definite ratio between the magnitudes of $\vec{E}$ and $\vec{B}$: $E = cB$.
3. The wave travels in vacuum with a definite and unchanging speed.
4. Unlike mechanical waves, which need the particles of a medium such as air to transmit a wave, electromagnetic waves require no medium.

Figure 32.9 A right-hand rule for electromagnetic waves relates the directions of $\vec{E}$ and $\vec{B}$ and the direction of propagation.

Right-hand rule for an electromagnetic wave:

(1) Point the thumb of your right hand in the wave's direction of propagation.

(2) Imagine rotating the $\vec{E}$-field vector 90° in the sense your fingers curl. That is the direction of the $\vec{B}$ field.



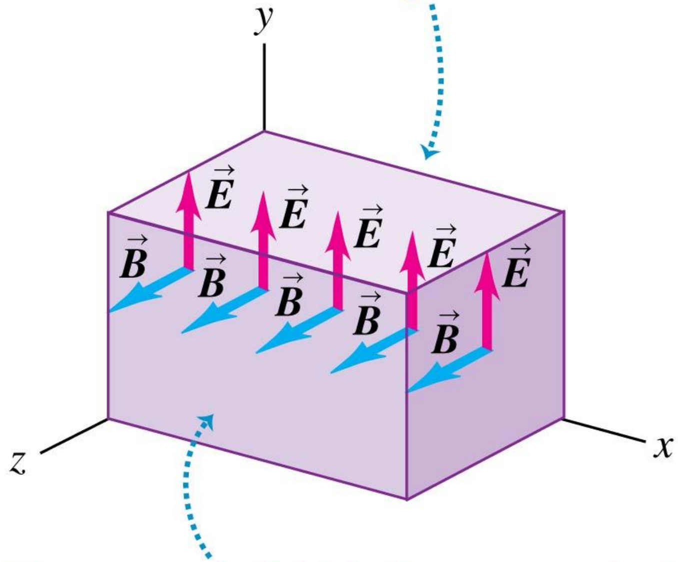
Direction of propagation = direction of $\vec{E} \times \vec{B}$.

Pearson

Gauss's Laws and the Simple Plane Wave -- Summary

- Shown is a Gaussian surface, a rectangular box, through which the simple plane wave is traveling.
- The box encloses no electric charge.
- In order to satisfy Maxwell's first and second equations, the electric and magnetic fields must be perpendicular to the direction of propagation; that is, the wave must be **transverse**.

The electric field is the same on the top and bottom sides of the Gaussian surface, so the total electric flux through the surface is zero.



The magnetic field is the same on the left and right sides of the Gaussian surface, so the total magnetic flux through the surface is zero.

Pearson

Faraday's Law and the Simple Plane Wave -- Summary

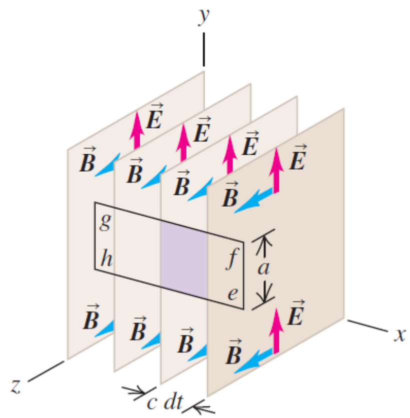
- The simple plane wave must satisfy Faraday's law in a vacuum.
- In a time *dt*, the magnetic flux through the rectangle in the *xy*-plane increases by an amount $d\Phi_B$.
- This increase equals the flux through the shaded rectangle with area *ac dt*; that is,

$$d\Phi_B = Bac\,dt.$$

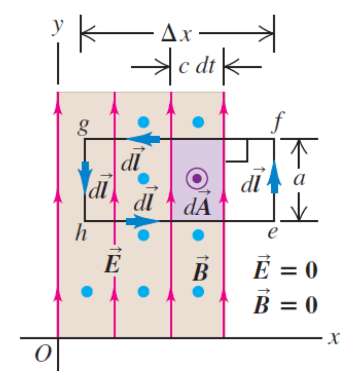
- Thus $d\Phi_B / dt = Bac$.
- This and Faraday's law imply:

Electromagnetic wave in vacuum: $E = cB$ (Electric-field magnitude E; Magnetic-field magnitude B; c: Speed of light in vacuum)

(a) In time *dt*, the wave front moves a distance *c dt* in the +*x*-direction.



(b) Side view of situation in (a)



Ampere's Law and the Simple Plane Wave -- Summary

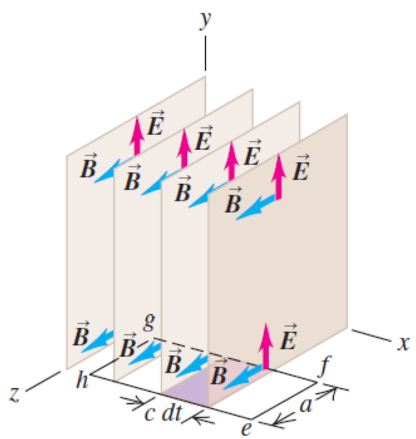
- The simple plane wave must satisfy Ampere's law in a vacuum. In a time *dt*, the electric flux through the rectangle in the *xz*-plane increases by an amount $d\Phi_E$.
- This increase equals the flux through the shaded rectangle with area *ac dt*; that is, $d\Phi_E = Eac\,dt$.
- Thus $d\Phi_E / dt = Eac$. This implies:

Electromagnetic wave in vacuum:

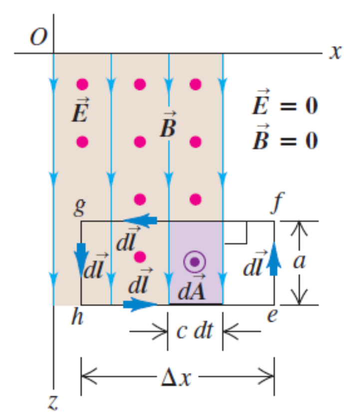
$$B = \epsilon_0 \mu_0 c E$$

Magnetic-field magnitude (B); Electric-field magnitude (E); Electric constant (ϵ_0); Magnetic constant (μ_0); Speed of light in vacuum (c)

(a) In time *dt*, the wave front moves a distance *c dt* in the +*x*-direction.



(b) Top view of situation in (a)



Properties of Electromagnetic Waves (1 of 2) -- Summary

- Maxwell's equations imply that in an electromagnetic wave, both the electric and magnetic fields are perpendicular to the direction of propagation of the wave, and to each other.
- In an electromagnetic wave, there is a definite ratio between the magnitudes of the electric and magnetic fields: $E = cB$.
- Unlike mechanical waves, electromagnetic waves require no medium. In fact, they travel in vacuum with a definite and unchanging speed:

Speed of electromagnetic waves in vacuum

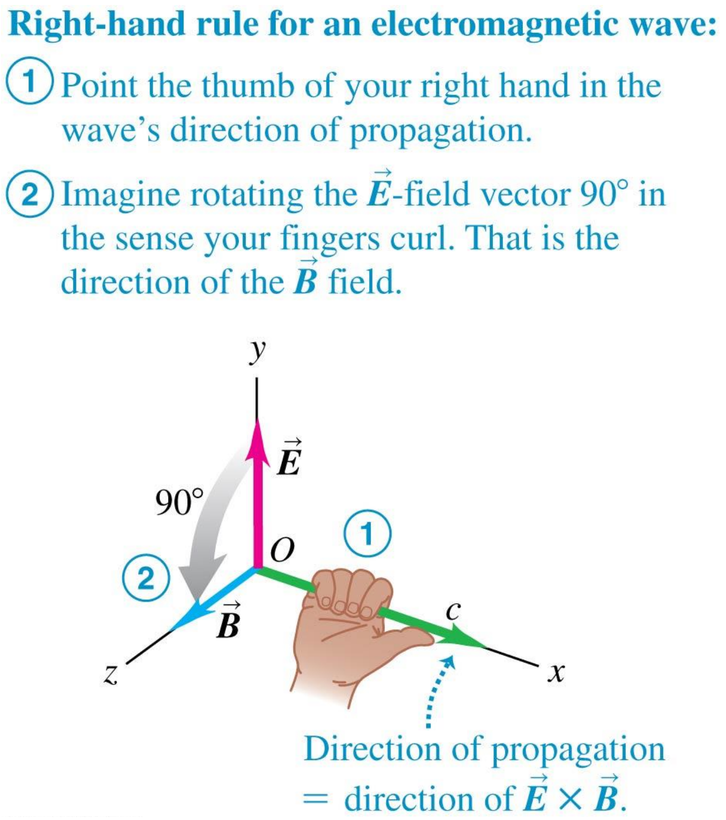
$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

Electric constant (ϵ_0)
Magnetic constant (μ_0)

- Inserting the numerical values of these constants, we obtain $c = 3.00 \times 10^8$ m/s.

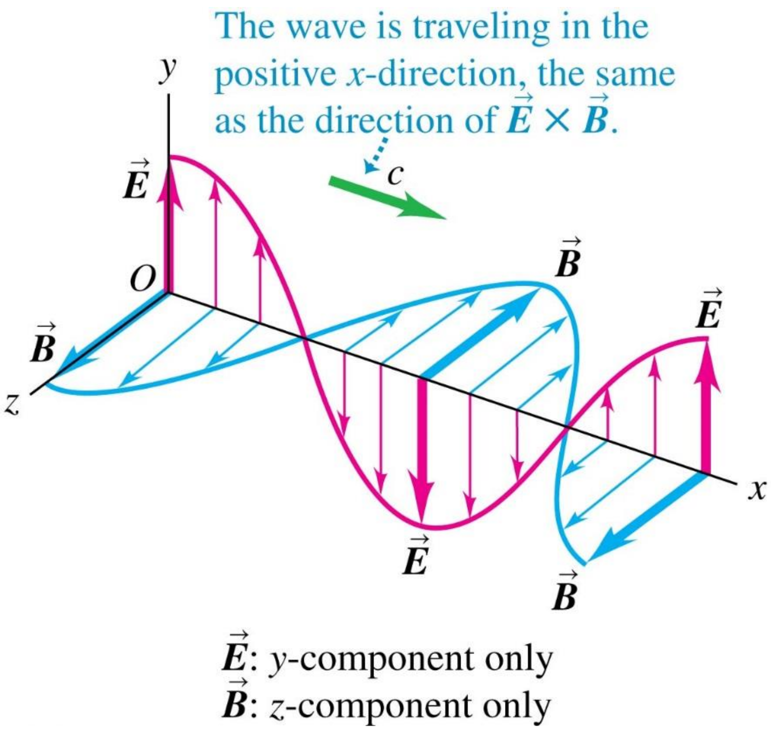
Properties of Electromagnetic Waves (2 of 2) -- Summary

- The direction of propagation of an electromagnetic wave is the direction of the vector product of the electric and magnetic fields.



Fields of a Sinusoidal Wave (1 of 3)

- Shown is a linearly polarized sinusoidal electromagnetic wave traveling in the +*x*-direction.
- One wavelength of the wave is shown at time $t = 0$.
- The fields are shown for only a few points along the *x*-axis.



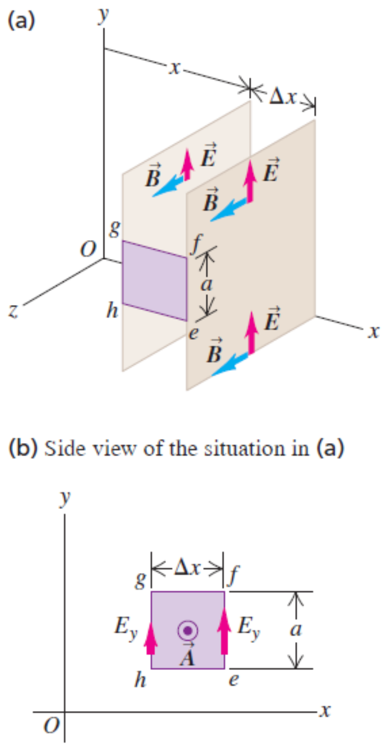
Pearson

Derivation of the Electromagnetic Wave Equation

During our discussion of mechanical waves in Section 15.3, we showed that a function $y(x, t)$ that represents the displacement of any point in a mechanical wave traveling along the x-axis must satisfy a differential equation, Eq. (15.12):

$$\frac{\partial^2 y(x, t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y(x, t)}{\partial t^2} \tag{32.10}$$

Figure 32.10 Faraday's law applied to a rectangle with height a and width Δx parallel to the xy-plane.



$$\oint \vec{E} \cdot d\vec{l} = -E_y(x, t)a + E_y(x + \Delta x, t)a$$
$$= a[E_y(x + \Delta x, t) - E_y(x, t)] \qquad (32.11)$$

To find the magnetic flux Φ_B through this rectangle, we assume that Δx is small enough that B_z is nearly uniform over the rectangle. In that case, $\Phi_B = B_z(x, t)A = B_z(x, t)a\,\Delta x$, and

$$\frac{d\Phi_B}{dt} = \frac{\partial B_z(x, t)}{\partial t} a\,\Delta x$$

We use partial-derivative notation because B_z is a function of both x and t. When we substitute this expression and Eq. (32.11) into Faraday's law, Eq. (32.1), we get

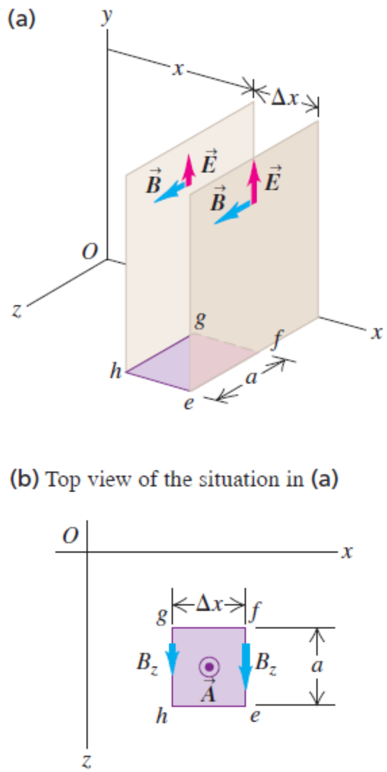
$$a[E_y(x + \Delta x, t) - E_y(x, t)] = -\frac{\partial B_z}{\partial t} a\,\Delta x$$
$$\frac{E_y(x + \Delta x, t) - E_y(x, t)}{\Delta x} = -\frac{\partial B_z}{\partial t}$$

Finally, imagine shrinking the rectangle down to a sliver so that Δx approaches zero. When we take the limit of this equation as $\Delta x \rightarrow 0$, we get

$$\frac{\partial E_y(x, t)}{\partial x} = -\frac{\partial B_z(x, t)}{\partial t} \qquad (32.12)$$

Pearson

Figure 32.11 Ampere's law applied to a rectangle with height a and width Δx parallel to the xz-plane.



Next we apply Ampere's law to the rectangle shown in **Fig. 32.11**. The line integral $\oint \vec{B} \cdot d\vec{l}$ becomes

$$\oint \vec{B} \cdot d\vec{l} = -B_z(x + \Delta x, t)a + B_z(x, t)a \qquad (32.13)$$

$$\oint \vec{B} \cdot d\vec{l} = -B_z(x + \Delta x, t)a + B_z(x, t)a \qquad (32.13)$$

Again assuming that the rectangle is narrow, we approximate the electric flux Φ_E through it as $\Phi_E = E_y(x, t)A = E_y(x, t)a\,\Delta x$. The rate of change of Φ_E, which we need for Ampere's law, is then

$$\frac{d\Phi_E}{dt} = \frac{\partial E_y(x, t)}{\partial t} a\,\Delta x$$

Now we substitute this expression and Eq. (32.13) into Ampere's law, Eq. (32.5):

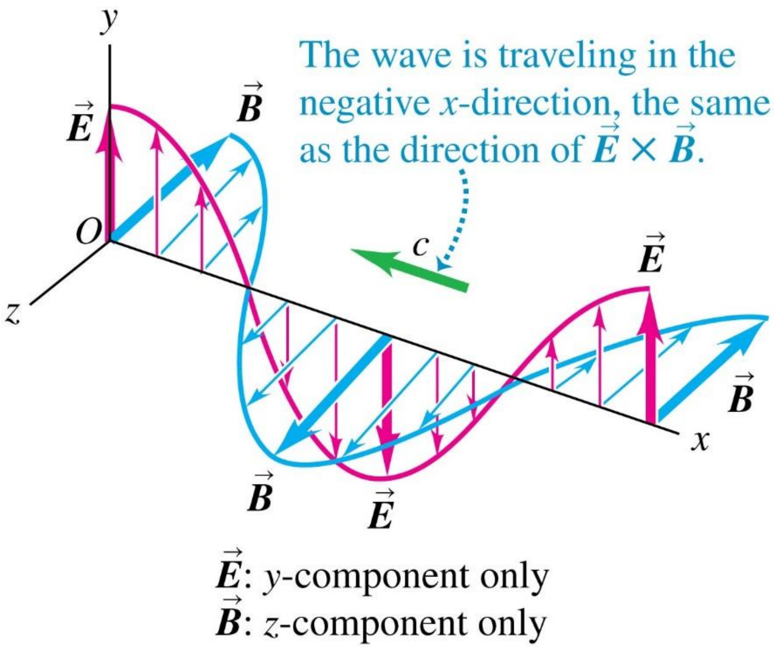
$$-B_z(x + \Delta x, t)a + B_z(x, t)a = \epsilon_0 \mu_0 \frac{\partial E_y(x, t)}{\partial t} a\,\Delta x$$

Again we divide both sides by $a\,\Delta x$ and take the limit as $\Delta x \rightarrow 0$. We find

$$-\frac{\partial B_z(x, t)}{\partial x} = \epsilon_0 \mu_0 \frac{\partial E_y(x, t)}{\partial t} \qquad (32.14)$$

Fields of a Sinusoidal Wave (2 of 3)

- Shown is a linearly polarized sinusoidal electromagnetic wave traveling in the −*x*-direction.
- One wavelength of the wave is shown at time $t = 0$.
- The fields are shown for only a few points along the *x*-axis.



Pearson

Sinusoidal Electromagnetic Waves

- Electromagnetic waves produced by an oscillating point charge are an example of sinusoidal waves that are not plane waves.
- But if we restrict our observations to a relatively small region of space at a sufficiently great distance from the source, even these waves are well approximated by plane waves.

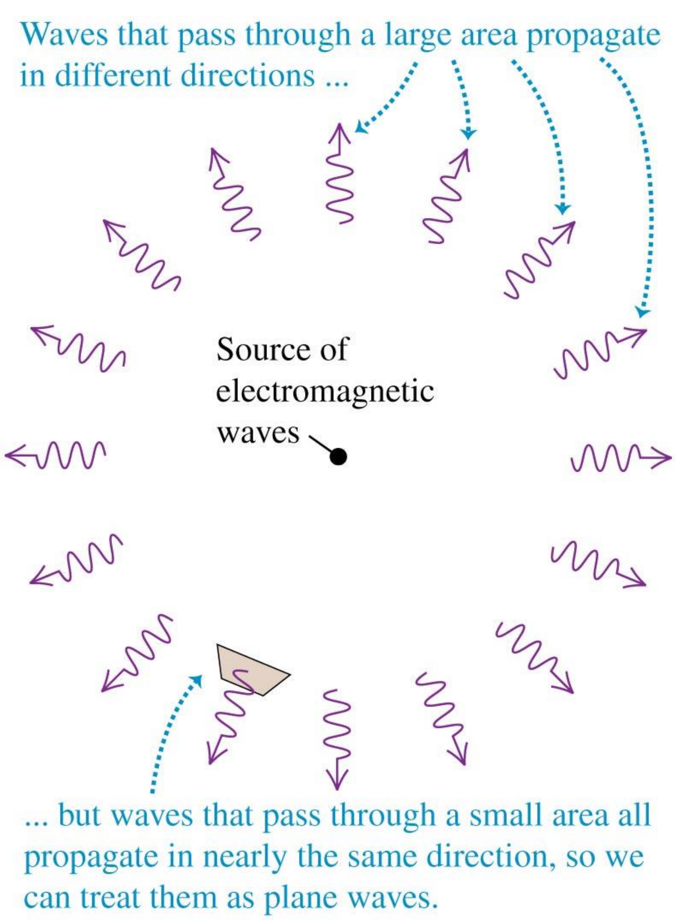
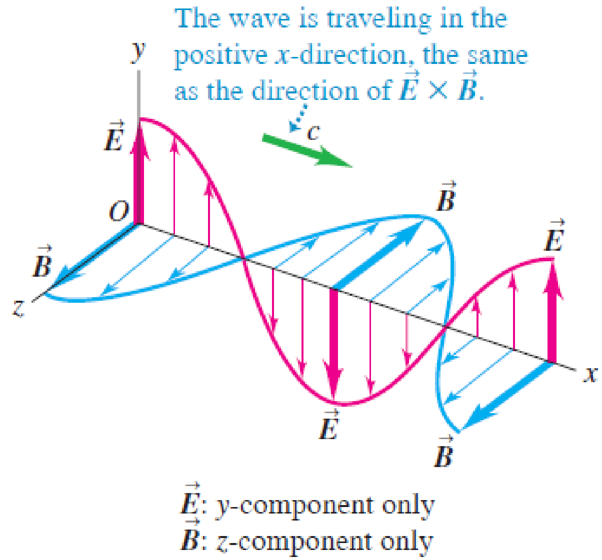


Figure 32.13 Representation of the electric and magnetic fields as functions of x for a linearly polarized sinusoidal plane electromagnetic wave. One wavelength of the wave is shown at time $t = 0$. The fields are shown for only a few points along the x-axis.



Fields of a Sinusoidal Wave (3 of 3)

- We can describe electromagnetic waves by means of wave functions:

Sinusoidal electromagnetic plane wave, propagating in $+x$-direction:

$$\vec{E}(x,t) = \hat{\jmath}E_{max}\cos(kx - \omega t)$$

$$\vec{B}(x,t) = \hat{k}B_{max}\cos(kx - \omega t)$$

Electric field; Electric-field magnitude; Wave number; Angular frequency; Magnetic field; Magnetic-field magnitude

- The wave travels to the right with speed $c = \frac{\omega}{k}$.
- The amplitudes must be related by:

Sinusoidal electromagnetic wave in vacuum:

$$E_{max} = cB_{max}$$

Electric-field amplitude; Magnetic-field amplitude; Speed of light in vacuum

- Video Tutor Solution: Example 32.1

Pearson

EXAMPLE 32.1 Electric and magnetic fields of a laser beam

A carbon dioxide laser emits a sinusoidal electromagnetic wave that travels in vacuum in the negative x-direction. The wavelength is 10.6 μm (in the infrared; see Fig. 32.4) and the $\vec{E}$ field is parallel to the z-axis, with $E_{max} = 1.5$ MV/m. Write vector equations for $\vec{E}$ and $\vec{B}$ as functions of time and position.

EXECUTE A possible pair of wave functions that describe the wave shown in Fig. 32.15 are

$$\vec{E}(x, t) = \hat{k}E_{max}\cos(kx + \omega t)$$
$$\vec{B}(x, t) = \hat{\jmath}B_{max}\cos(kx + \omega t)$$

The plus sign in the arguments of the cosine functions indicates that the wave is propagating in the negative x-direction, as it should. Faraday's law requires that $E_{max} = cB_{max}$ [Eq. (32.18)], so

$$B_{max} = \frac{E_{max}}{c} = \frac{1.5 \times 10^6 \text{ V/m}}{3.0 \times 10^8 \text{ m/s}} = 5.0 \times 10^{-3} \text{ T}$$

(Recall that 1 V = 1 Wb/s and 1 Wb/m^2 = 1 T.)

We have $\lambda = 10.6 \times 10^{-6}$ m, so the wave number and angular frequency are

$$k = \frac{2\pi}{\lambda} = \frac{2\pi \text{ rad}}{10.6 \times 10^{-6} \text{ m}} = 5.93 \times 10^5 \text{ rad/m}$$

$$\omega = ck = (3.00 \times 10^8 \text{ m/s})(5.93 \times 10^5 \text{ rad/m})$$
$$= 1.78 \times 10^{14} \text{ rad/s}$$

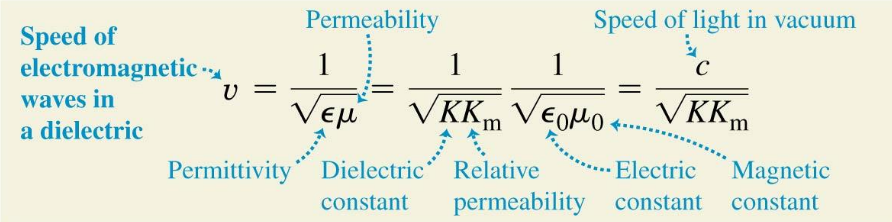
Substituting these values into the above wave functions, we get

$$\vec{E}(x, t) = \hat{k}(1.5 \times 10^6 \text{ V/m}) \times \cos[(5.93 \times 10^5 \text{ rad/m})x + (1.78 \times 10^{14} \text{ rad/s})t]$$

$$\vec{B}(x, t) = \hat{j}(5.0 \times 10^{-3}\ \text{T}) \times \cos[(5.93 \times 10^{5}\ \text{rad/m})x + (1.78 \times 10^{14}\ \text{rad/s})t]$$

Electromagnetic Waves in Matter

- Electromagnetic waves can travel in certain types of matter, such as air, water, or glass.
- When electromagnetic waves travel in nonconducting materials—that is, dielectrics—the speed *v* of the waves depends on the dielectric constant of the material.



$$v = \frac{1}{\sqrt{\epsilon\mu}} = \frac{1}{\sqrt{KK_m}}\frac{1}{\sqrt{\epsilon_0\mu_0}} = \frac{c}{\sqrt{KK_m}}$$

- The ratio of the speed *c* in vacuum to the speed *v* in a material is known in optics as the **index of refraction** *n* of the material.

$$\frac{c}{v} = n = \sqrt{KK_m} \cong \sqrt{K}$$

Pearson

(a) Visiting a jewelry store one evening, you hold a diamond up to the light of a sodium-vapor street lamp. The heated sodium vapor emits yellow light with a frequency of 5.09×10^{14} Hz. Find the wavelength in vacuum and the wave speed and wavelength in diamond, for which $K = 5.84$ and $K_m = 1.00$ at this frequency. (b) A 90.0 MHz radio wave (in the FM radio band) passes from vacuum into an insulating ferrite (a ferromagnetic material used in computer cables to suppress radio interference). Find the wavelength in vacuum and the wave speed and wavelength in the ferrite, for which $K = 10.0$ and $K_m = 1000$ at this frequency.

EXECUTE (a) The wavelength in vacuum of the sodium light is

$$\lambda_{\text{vacuum}} = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{5.09 \times 10^{14} \text{ Hz}} = 5.89 \times 10^{-7} \text{ m} = 589 \text{ nm}$$

The wave speed and wavelength in diamond are

$$v_{\text{diamond}} = \frac{c}{\sqrt{KK_{\text{m}}}} = \frac{3.00 \times 10^8 \text{ m/s}}{\sqrt{(5.84)(1.00)}} = 1.24 \times 10^8 \text{ m/s}$$

$$\lambda_{\text{diamond}} = \frac{v_{\text{diamond}}}{f} = \frac{1.24 \times 10^8 \text{ m/s}}{5.09 \times 10^{14} \text{ Hz}} = 2.44 \times 10^{-7} \text{ m} = 244 \text{ nm}$$

(b) Following the same steps as in part (a), we find

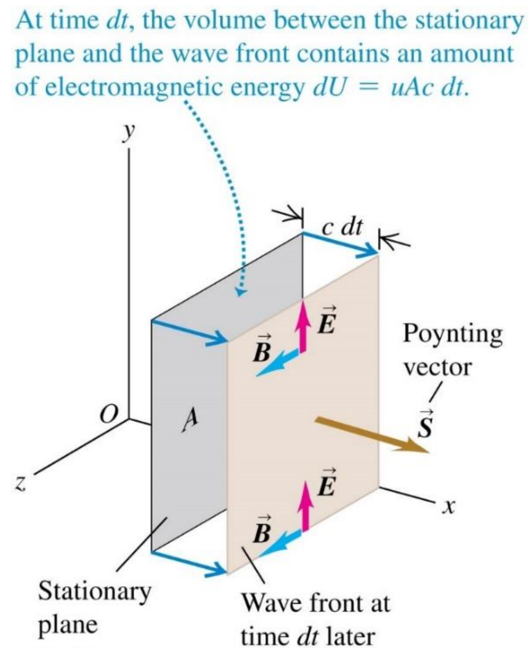
$$\lambda_{\text{vacuum}} = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{90.0 \times 10^6 \text{ Hz}} = 3.33 \text{ m}$$

$$v_{\text{ferrite}} = \frac{c}{\sqrt{KK_{\text{m}}}} = \frac{3.00 \times 10^8 \text{ m/s}}{\sqrt{(10.0)(1000)}} = 3.00 \times 10^6 \text{ m/s}$$

$$\lambda_{\text{ferrite}} = \frac{v_{\text{ferrite}}}{f} = \frac{3.00 \times 10^6 \text{ m/s}}{90.0 \times 10^6 \text{ Hz}} = 3.33 \times 10^{-2} \text{ m} = 3.33 \text{ cm}$$

Energy in Electromagnetic Waves (1 of 2)

- Electromagnetic waves such as those we have described are traveling waves that transport energy from one region to another.
- The British physicist John Poynting introduced the **Poynting vector**, $\vec{S}$.
- The magnitude of the Poynting vector is the power per unit area in the wave, and it points in the direction of propagation.



Poynting vector in vacuum $\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$ (Electric field: $\vec{E}$; Magnetic field: $\vec{B}$; Magnetic constant: μ_0)

- Video Tutor Solution: Example 32.6

Pearson

Energy in Electromagnetic Waves (2 of 2)

- The magnitude of the average value of $\vec{S}$ is called the **intensity**. The SI unit of intensity is $1\,\text{W/m}^2$.
- These rooftop solar panels are tilted to be face-on to the sun so that the panels can absorb the maximum amount of wave energy.

Intensity of a sinusoidal electromagnetic wave in vacuum

$$I = S_{av} = \frac{E_{max}B_{max}}{2\mu_0} = \frac{E_{max}{}^2}{2\mu_0 c} = \frac{1}{2}\sqrt{\frac{\epsilon_0}{\mu_0}}E_{max}{}^2 = \frac{1}{2}\epsilon_0 c E_{max}{}^2$$

Electric-field amplitude (E_{max}); Magnetic-field amplitude (B_{max}); Electric constant (ϵ_0); Magnitude of average Poynting vector (S_{av}); Magnetic constant (μ_0); Speed of light in vacuum (c)

Pearson

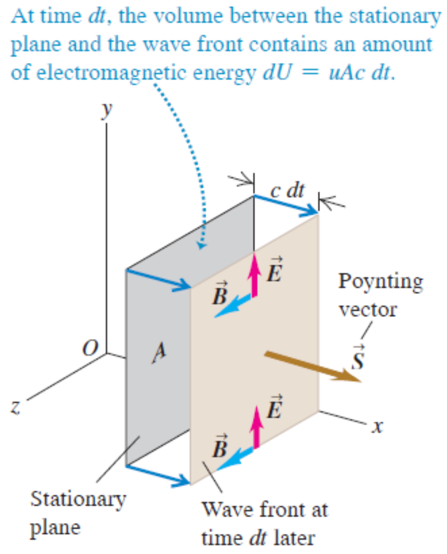
For electromagnetic waves in vacuum, the magnitudes E and B are related by

$$B = \frac{E}{c} = \sqrt{\epsilon_0 \mu_0} E \qquad (32.24)$$

Combining Eqs. (32.23) and (32.24), we can also express the energy density u in a simple electromagnetic wave in vacuum as

$$u = \tfrac{1}{2}\epsilon_0 E^2 + \frac{1}{2\mu_0}\left(\sqrt{\epsilon_0 \mu_0} E\right)^2 = \epsilon_0 E^2 \qquad (32.25)$$

Figure 32.17 A wave front at a time dt after it passes through the stationary plane with area A.



Poynting vector in vacuum: $\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$ (32.28)

Electric field: $\vec{E}$; Magnetic field: $\vec{B}$; Magnetic constant: μ_0

$$P = \oint \vec{S} \cdot d\vec{A}$$

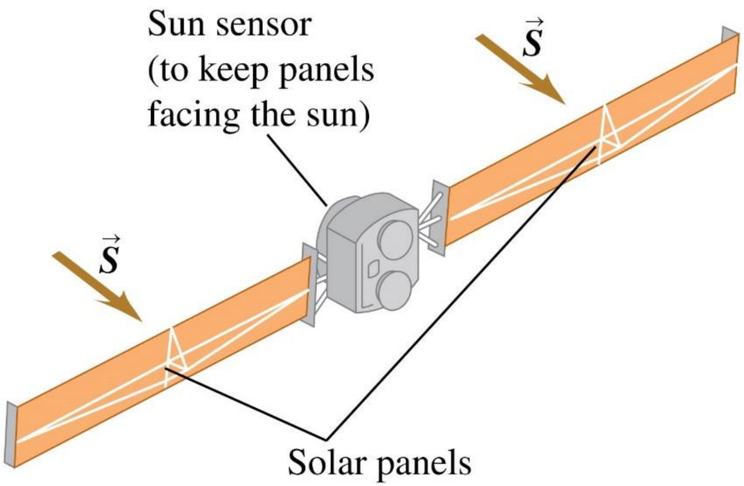
Electromagnetic Radiation Pressure

- Electromagnetic waves carry momentum and can therefore exert **radiation pressure** on a surface:

$$p_{rad} = \frac{S_{av}}{c} = \frac{I}{c} \text{ (radiation pressure, wave totally absorbed)}$$

$$p_{rad} = \frac{2S_{av}}{c} = \frac{2I}{c} \text{ (radiation pressure, wave totally absorbed)}$$

- For example, if the solar panels on an earth-orbiting satellite are perpendicular to the sunlight, and the radiation is completely absorbed, the average radiation pressure is $4.7 \times 10^{-6}\ \text{N/m}^2$.



EXAMPLE 32.4 Energy in a sinusoidal wave

A radio station on the earth's surface emits a sinusoidal wave with average total power 50 kW (**Fig. 32.19**). Assuming that the transmitter radiates equally in all directions above the ground (which is unlikely in real situations), find the electric-field and magnetic-field amplitudes E_{max} and B_{max} detected by a satellite 100 km from the antenna.