Chapter 32

Electromagnetic Waves

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Goals for Chapter 32

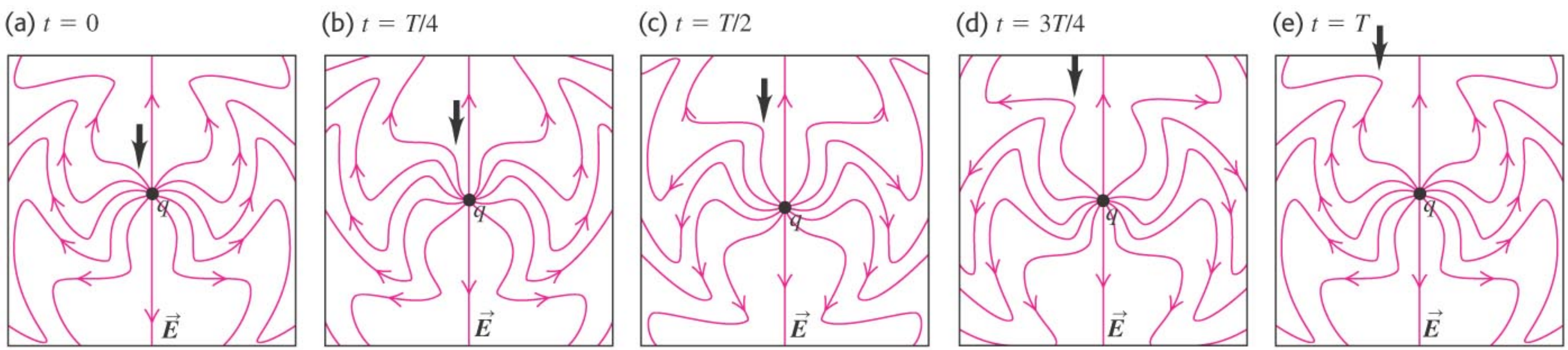
- To learn why a light wave contains both electric and magnetic fields
- To relate the speed of light to the fundamental constants of electromagnetism
- To describe electromagnetic waves
- To determine the power carried by electromagnetic waves
- To describe standing electromagnetic waves

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.

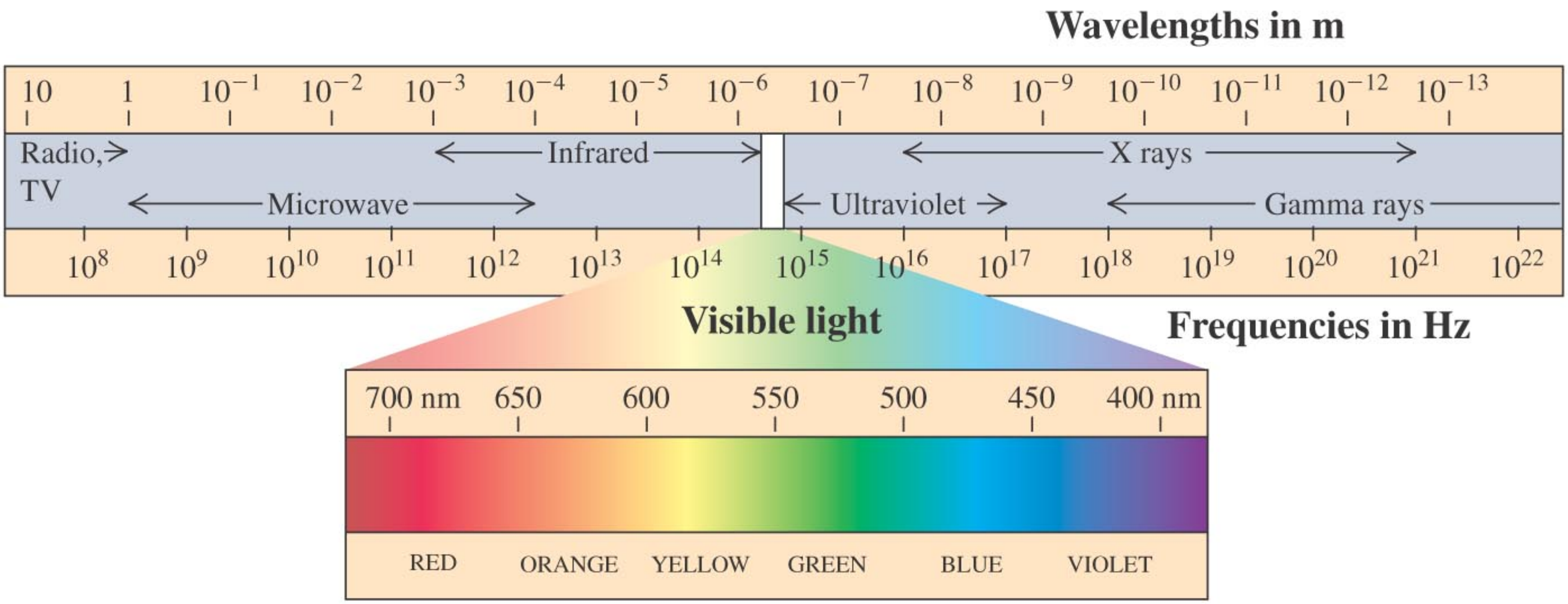
Maxwell's equations and electromagnetic waves

- Maxwell's equations predicted that an oscillating charge emits *electromagnetic radiation* in the form of electromagnetic waves.
- Figure 32.3 below shows the electric field lines of a point charge undergoing simple harmonic motion.



The electromagnetic spectrum

- The *electromagnetic spectrum* includes electromagnetic waves of all frequencies and wavelengths. (See Figure 32.4 below.)



Visible light

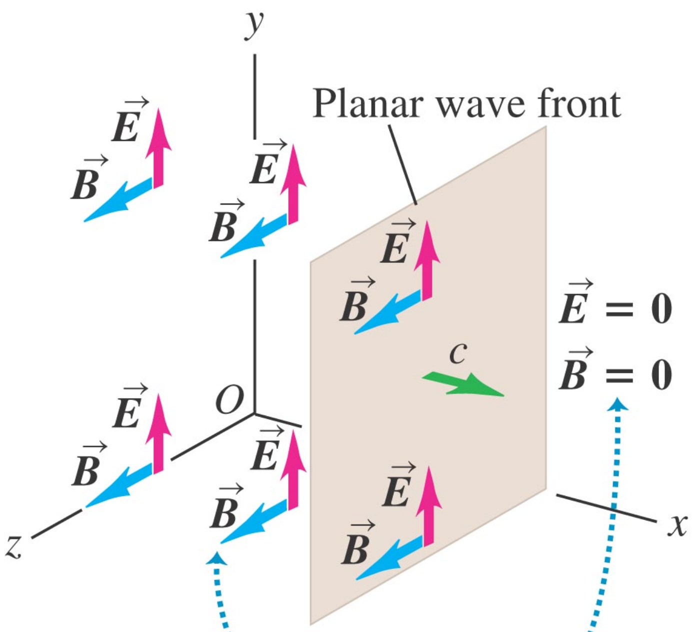
- *Visible light* is the segment of the electromagnetic spectrum that we can see.
- Visible light extends from the violet end (400 nm) to the red end (700 nm), as shown in Table 32.1.

Table 32.1 Wavelengths of Visible Light

400 to 440 nm	Violet
440 to 480 nm	Blue
480 to 560 nm	Green
560 to 590 nm	Yellow
590 to 630 nm	Orange
630 to 700 nm	Red

Plane electromagnetic waves

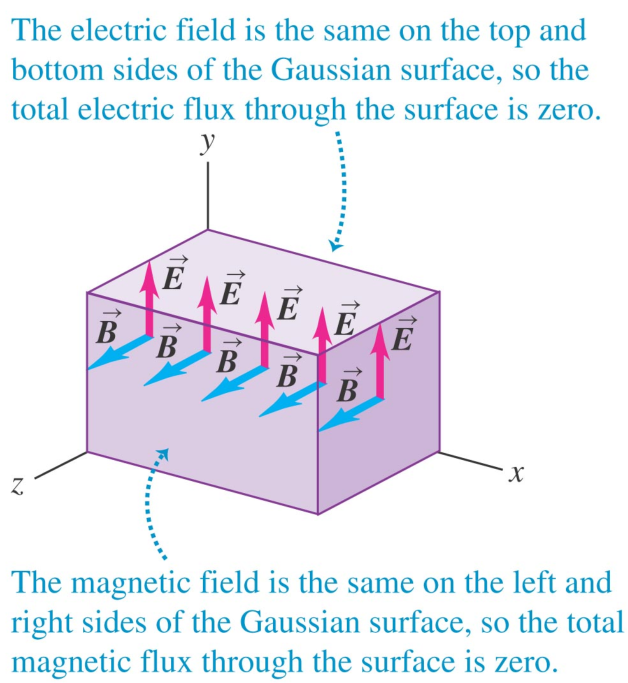
- A *plane wave* has a planar wave front. See Figure 32.5 below.

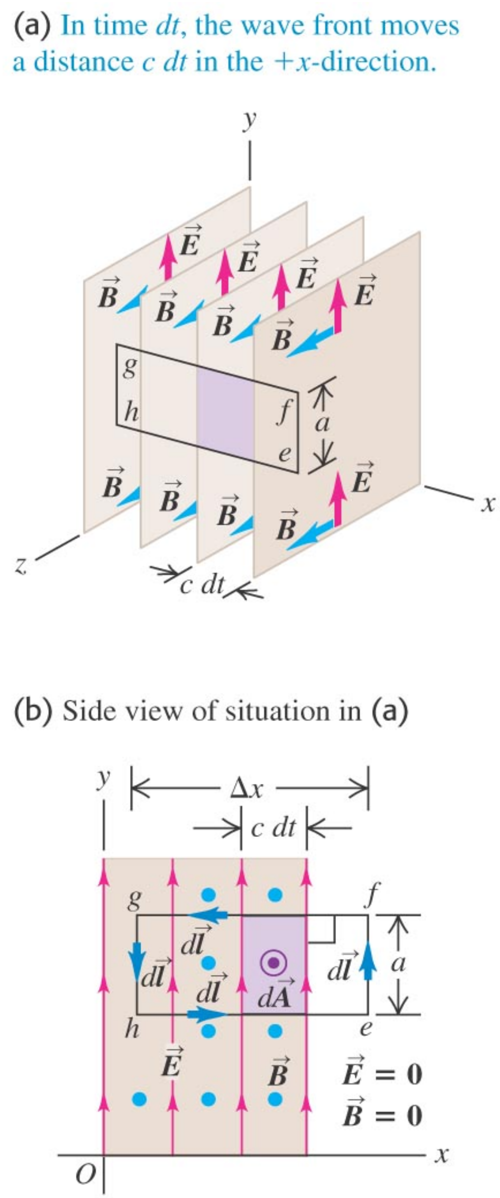


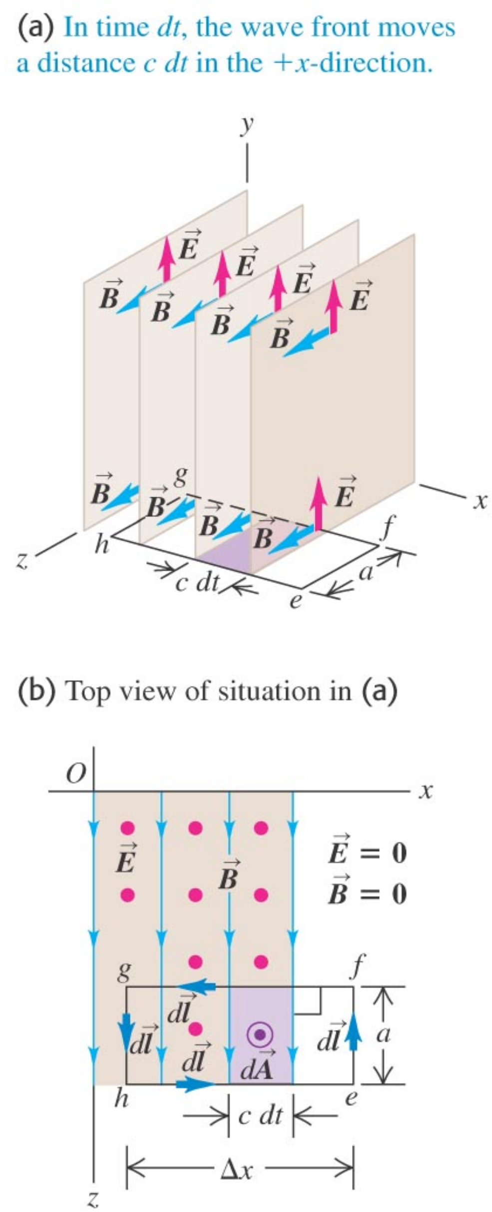
The electric and magnetic fields are uniform behind the advancing wave front and zero in front of it.

A simple plane electromagnetic wave

- Follow the text discussion of a simple plane electromagnetic wave using Figures 32.6, 32.7, and 32.8 shown here.







Key properties of electromagnetic waves

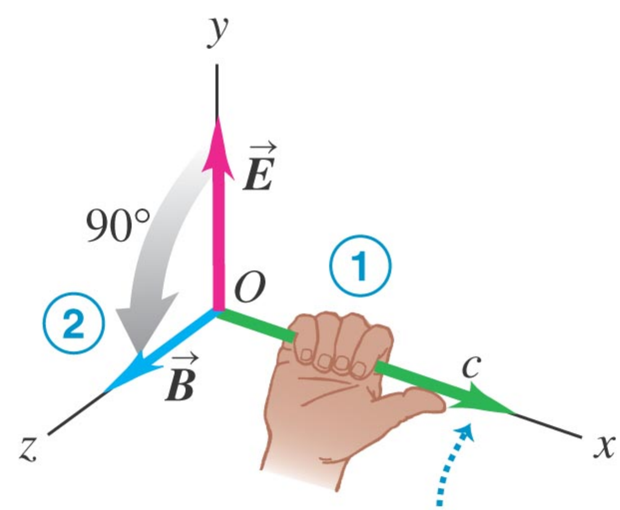
- The magnitudes of the fields in vacuum are related by $E = cB$.
- The speed of the waves is $c = 3.00 \times 10^8$ m/s in vacuum.
- The waves are *transverse.* Both fields are perpendicular to the direction of propagation and to each other. (See Figure 32.9 at the right.)

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.

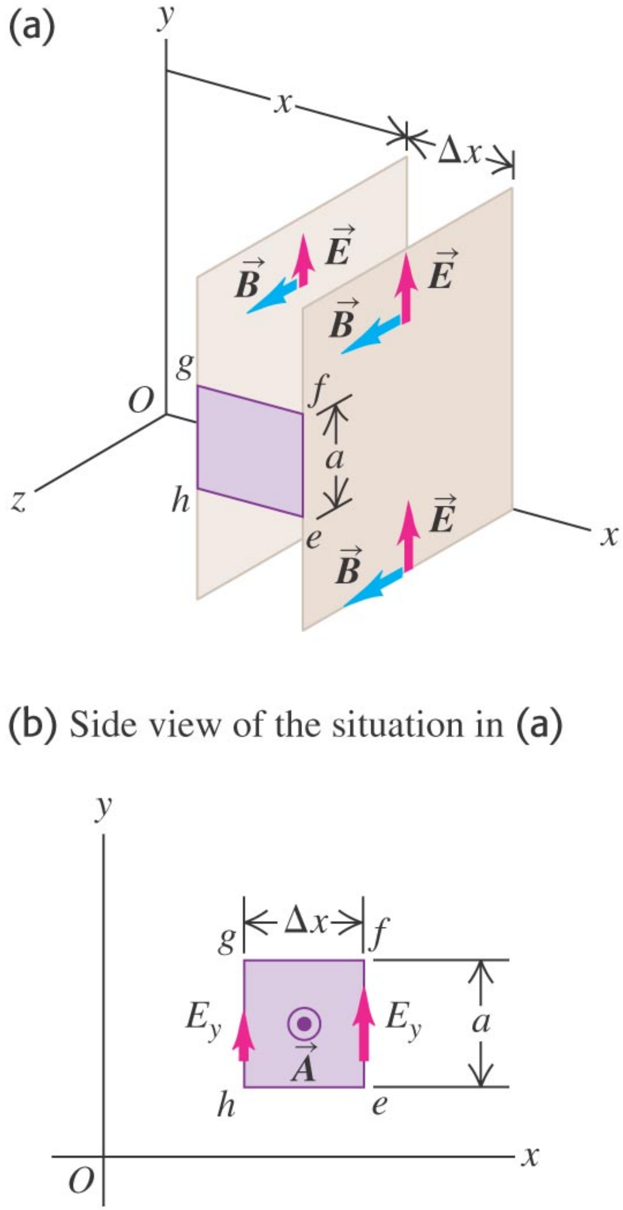
That is the direction of the $\vec{B}$ field.

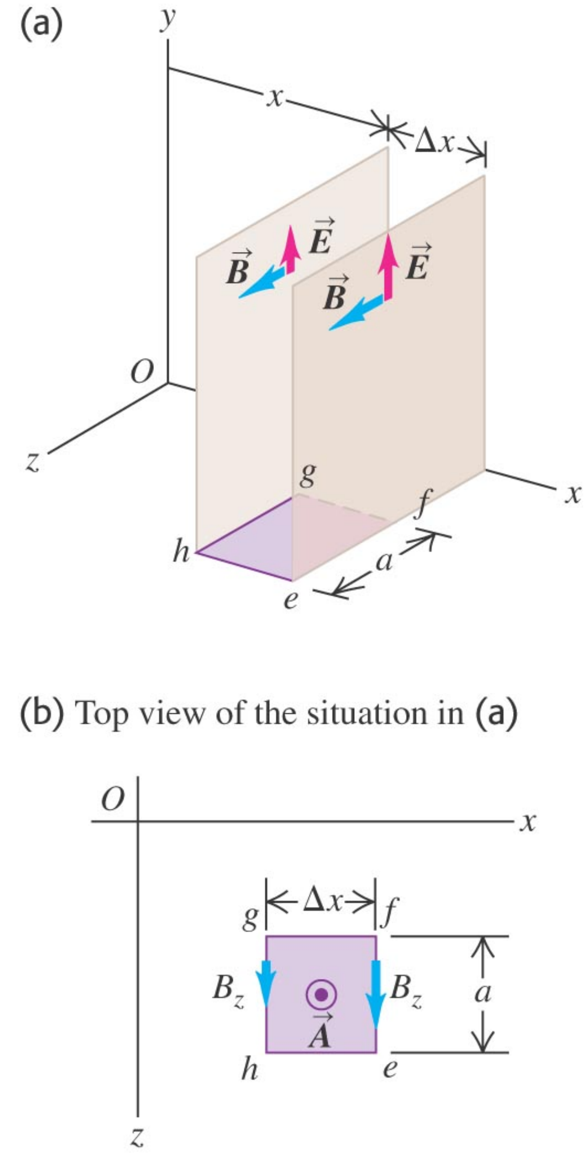


Direction of propagation $=$ direction of $\vec{E} \times \vec{B}$.

Derivation of the electromagnetic wave equation

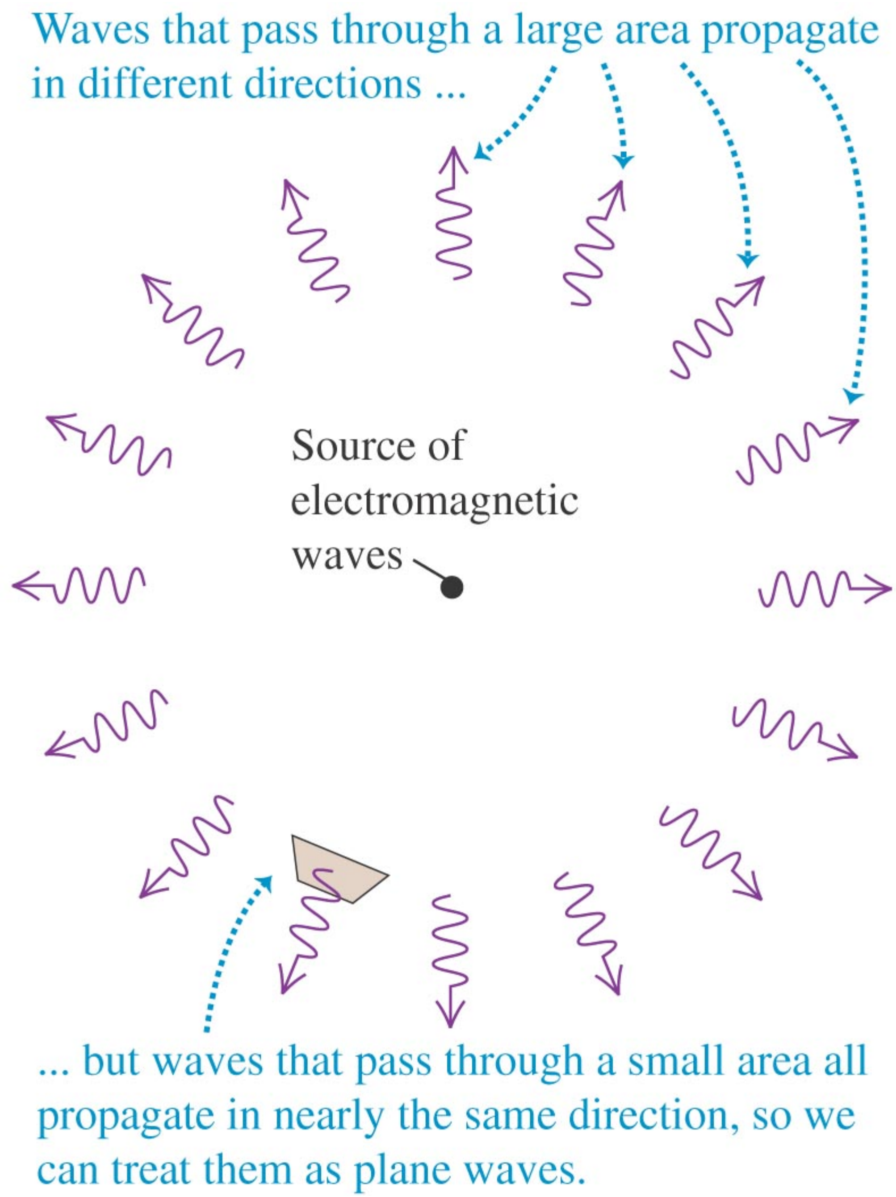
- Follow the text derivation of the electromagnetic wave equation.
- Figure 32.10 (left) applies to Faraday's law.
- Figure 32.11 (right) applies to Ampere's law.





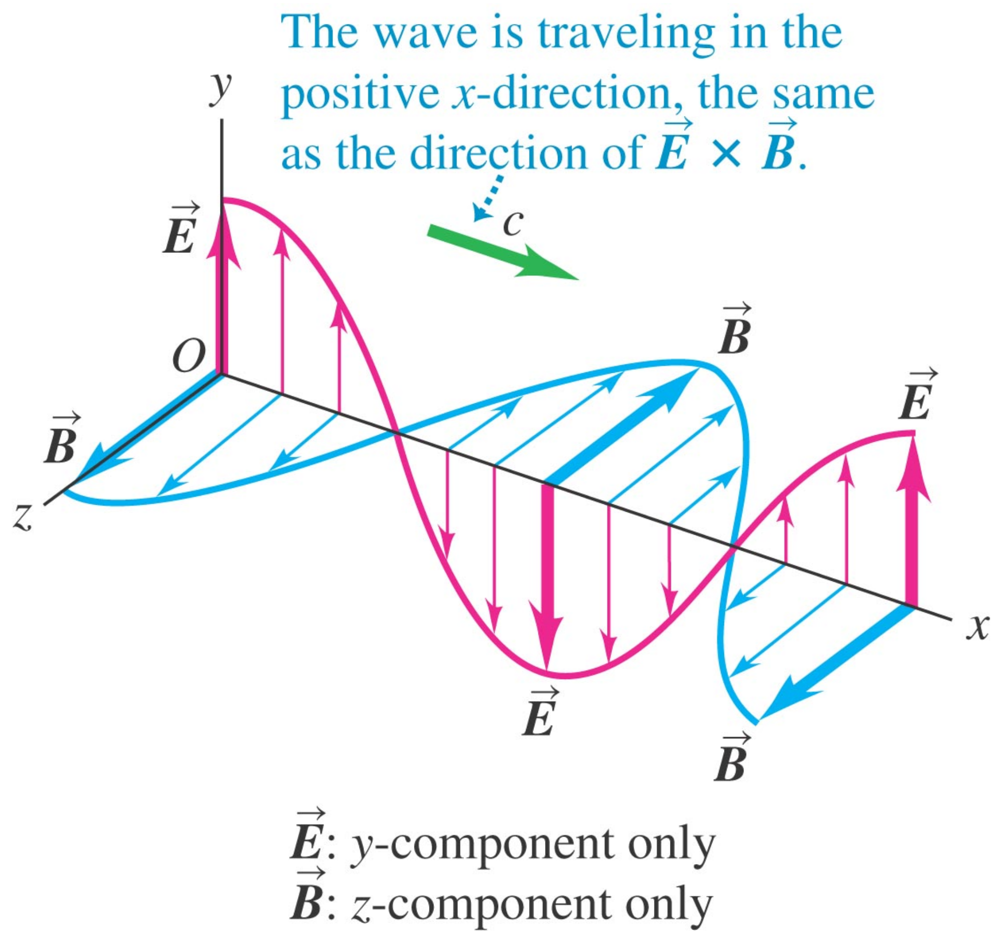
Sinusoidal electromagnetic waves

- Waves passing through a small area far from a source can be treated as plane waves. (See Figure 32.12 at the right.)



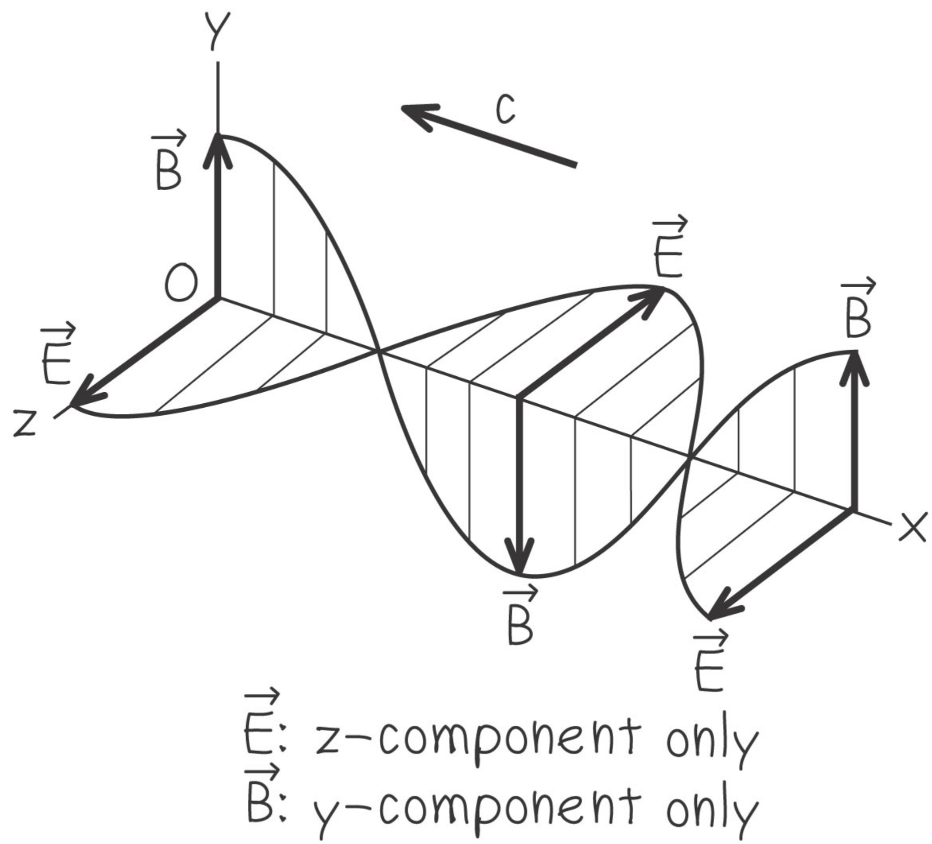
Fields of a sinusoidal wave

- Figure 32.13 (right) represents the electric and magnetic fields for a sinusoidal wave.
- Follow the text analysis of sinusoidal electromagnetic waves.



Fields of a laser beam

- Read Problem-Solving Strategy 32.1.
- Follow Example 32.1 using Figure 32.15 below.

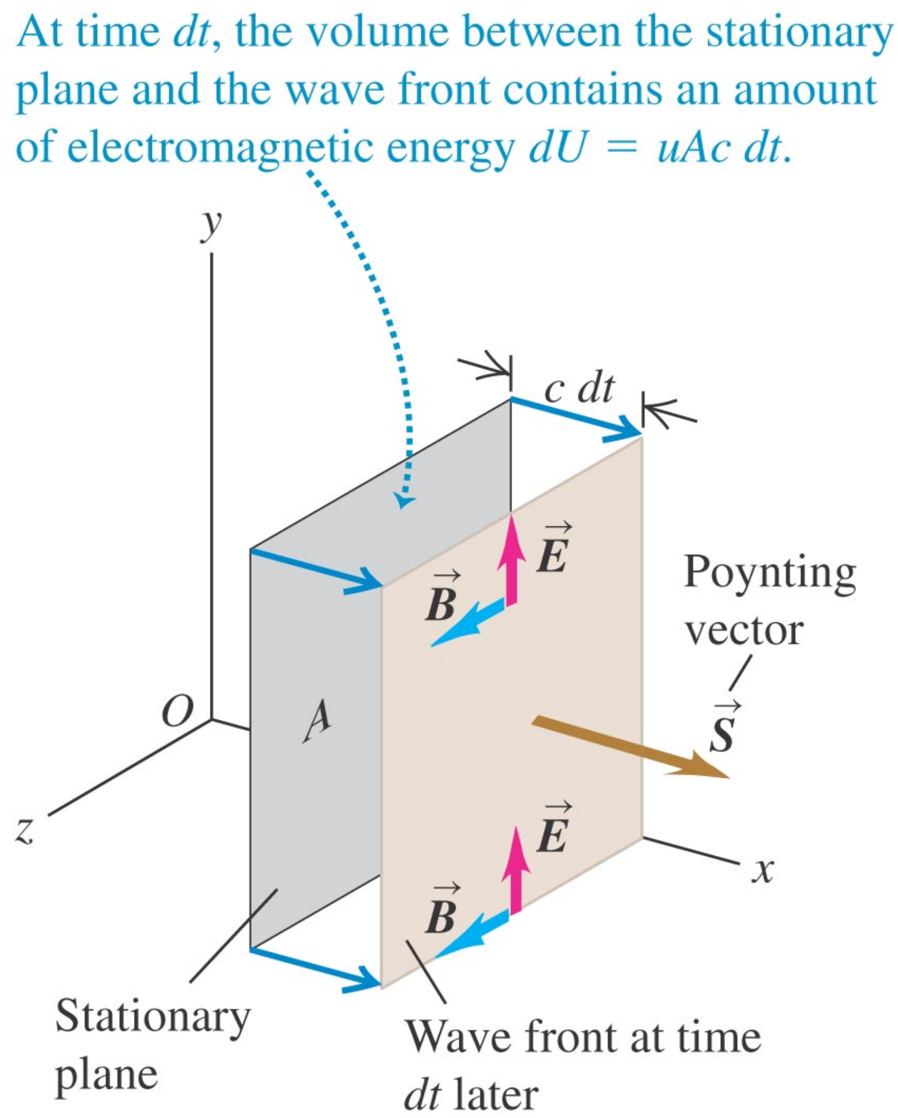


Electromagnetic waves in matter

- Follow the text analysis of electromagnetic waves in matter.
- The speed v of an electromagnetic wave in a material depends on the dielectric constant of the material.
- The *index of refraction* of a material is $n = c/v$.
- Follow Example 32.2.

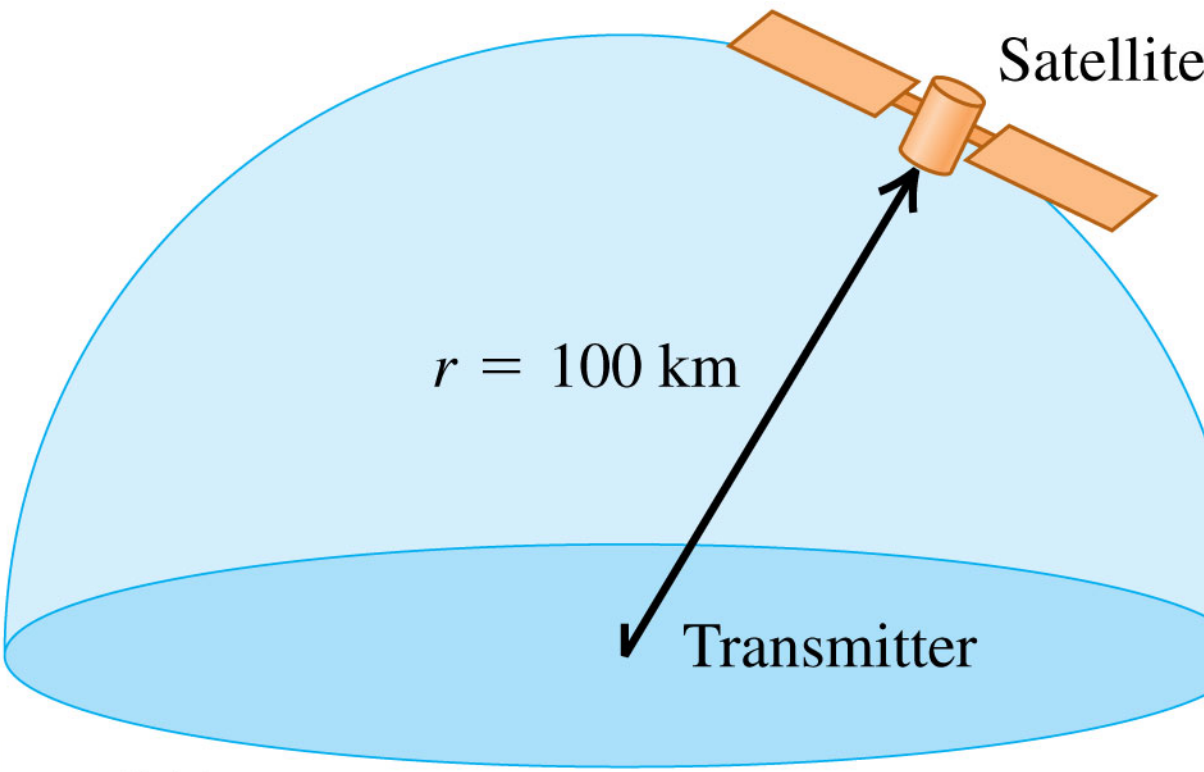
Energy in electromagnetic waves

- Follow the text analysis of electromagnetic energy flow and the Poynting vector. Use Figure 32.17 at the right.
- The magnitude of the *Poynting vector* is the power per unit area in the wave, and it points in the direction of propagation.
- The *intensity* of a sinusoidal electromagnetic wave is the time average of the Poynting vector.



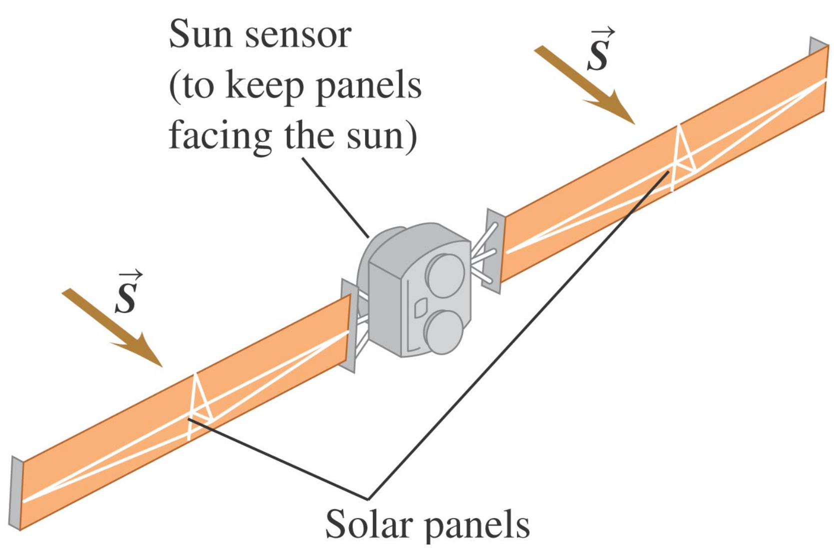
Energy in sinusoidal and nonsinusoidal waves

- Follow Example 32.3 for a nonsinusoidal wave.
- Follow Example 32.4 for a sinusoidal wave. Use Figure 32.19 below.



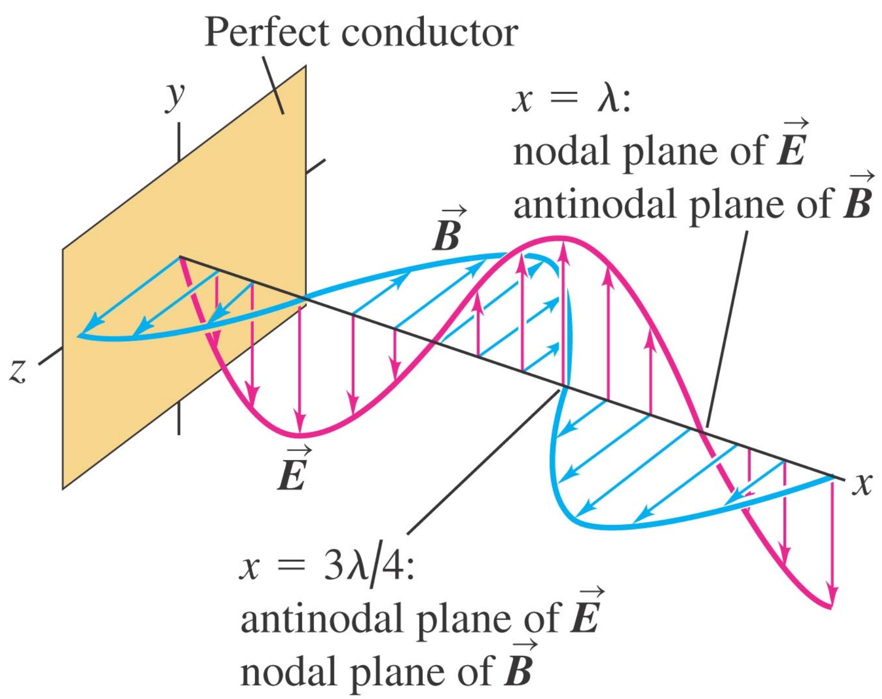
Electromagnetic momentum and radiation pressure

- Electromagnetic waves carry momentum and can therefore exert *radiation pressure* on a surface.
- Follow the text analysis of electromagnetic momentum flow and radiation pressure.
- Follow Example 32.5 using Figure 32.21 below.



Standing electromagnetic waves

- Electromagnetic waves can be reflected by a conductor or dielectric, which can lead to *standing waves*. (See Figure 32.22 below.)
- Follow the text analysis of standing electromagnetic waves.
- Follow Example 32.6 and Example 32.7.



Q32.1

In a vacuum, red light has a wavelength of 700 nm and violet light has a wavelength of 400 nm.

This means that in a vacuum, red light

A. has higher frequency and moves faster than violet light.

B. has higher frequency and moves slower than violet light.

C. has lower frequency and moves faster than violet light.

D. has lower frequency and moves slower than violet light.

E. none of the above

Q32.2

At a certain point in space, the electric and magnetic fields of an electromagnetic wave at a certain instant are given by

$$\vec{E} = \hat{i}\left(6\times10^{3}\ \text{V/m}\right)$$

$$\vec{B} = \hat{k}\left(2\times10^{-5}\ \text{T}\right)$$

This wave is propagating in the

A. positive *x*-direction.

B. negative *x*-direction.

C. positive *y*-direction.

D. negative *y*-direction.

E. none of the above

Q32.3

A sinusoidal electromagnetic wave in a vacuum is propagating in the positive *z*-direction.

At a certain point in the wave at a certain instant in time, the electric field points in the negative *x*-direction.

At the same point and at the same instant, the magnetic field points in the

A. positive *y*-direction.

B. negative *y*-direction.

C. positive *z*-direction.

D. negative *z*-direction.

E. none of the above

Q32.4

In a sinusoidal electromagnetic wave in a vacuum, the electric field has only an *x*-component. This component is given by

$E_x = E_{max} \cos(ky + wt)$

This wave propagates in the

A. positive *z*-direction.

B. negative *z*-direction.

C. positive *y*-direction.

D. negative *y*-direction.

E. none of the above

Q32.5

In a sinusoidal electromagnetic wave in a vacuum, the electric field has only an *x*-component. This component is given by

$E_x = E_{max} \cos(ky + wt)$

The magnetic field of this wave

A. has only an *x*-component.

B. has only a *y*-component.

C. has only a *z*-component.

D. not enough information given to decide

Q32.6

In a sinusoidal electromagnetic wave in a vacuum, the *magnetic* energy density

A. is the same at all points in the wave.

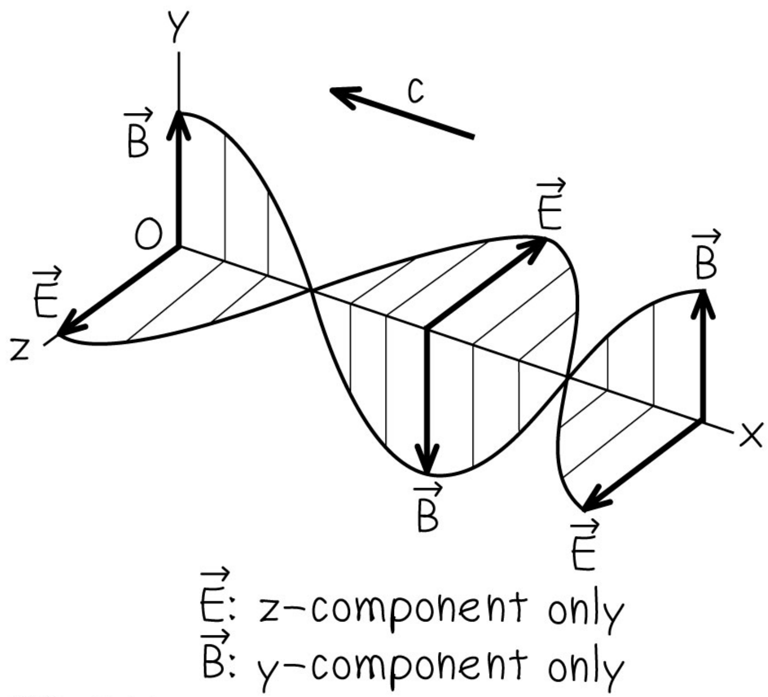
B. is maximum where the *electric* field has its greatest value.

C. is maximum where the *electric* field is zero.

D. none of the above

Q32.7

The drawing shows a sinusoidal electromagnetic wave in a vacuum at one instant of time at points between $x = 0$ and $x = l$. At this instant, at which values of x does the instantaneous Poynting vector have its maximum magnitude?



A. $x = 0$ and $x = l$ only

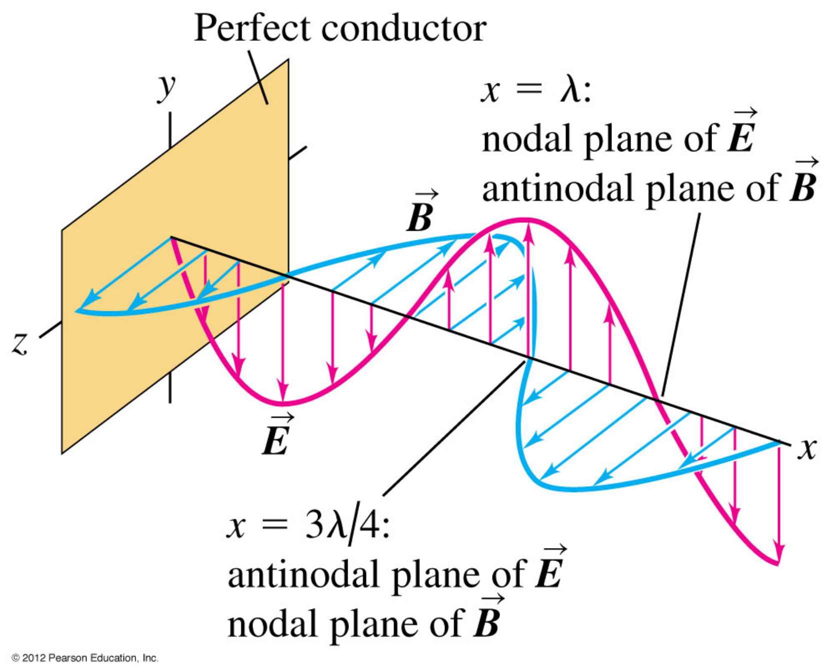
B. $x = l/4$ and $x = 3l/4$ only

C. $x = l/2$ only

D. $x = 0$, $x = l/2$, and $x = l$

Q32.8

The drawing shows a sinusoidal electromagnetic standing wave. The average Poynting vector in this wave



A. points along the *x*-axis.

B. points along the *y*-axis.

C. points along the *z*-axis.

D. is zero.

E. none of the above