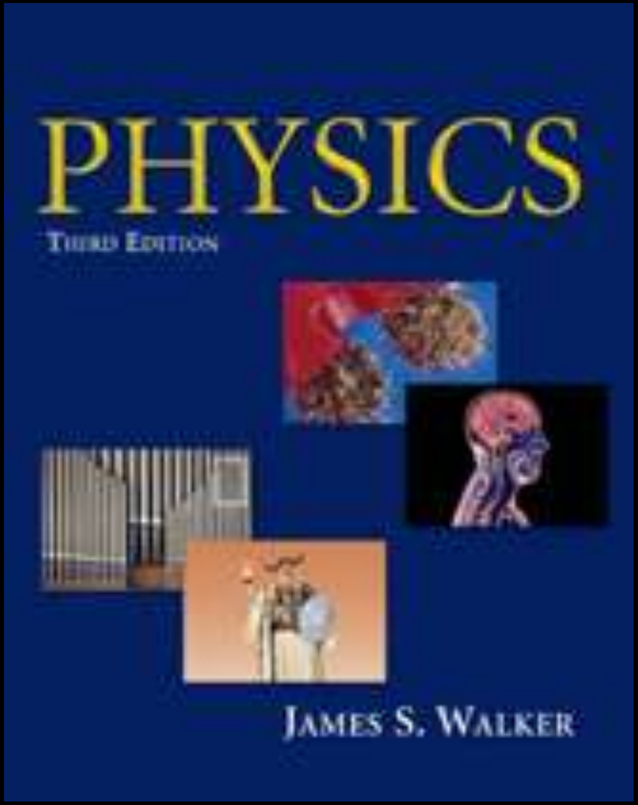


Lecture Outlines

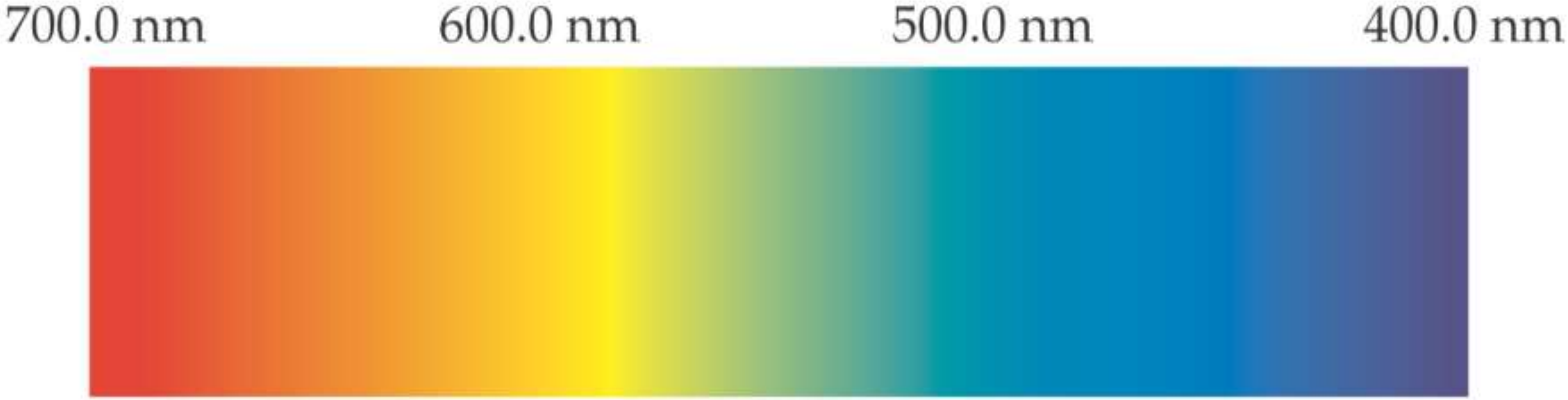
Chapter 25

Physics*, *3rd Edition

James S. Walker

Chapter 25

Electromagnetic Waves

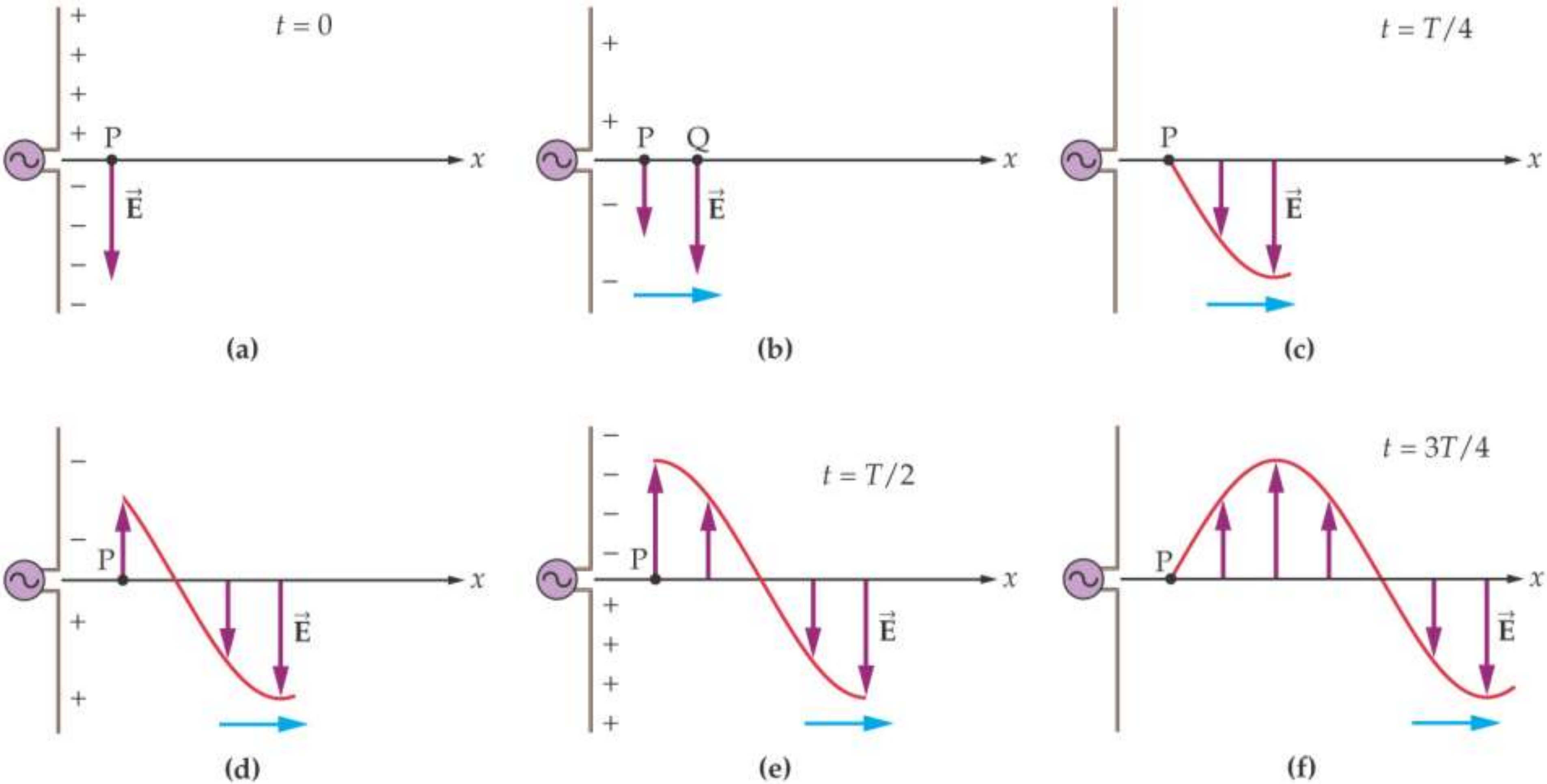


Units of Chapter 25

- The Production of Electromagnetic Waves
- The Propagation of Electromagnetic Waves
- The Electromagnetic Spectrum
- Energy and Momentum in Electromagnetic Waves
- Polarization

25-1 The Production of Electromagnetic Waves

Electromagnetic fields are produced by oscillating charges.



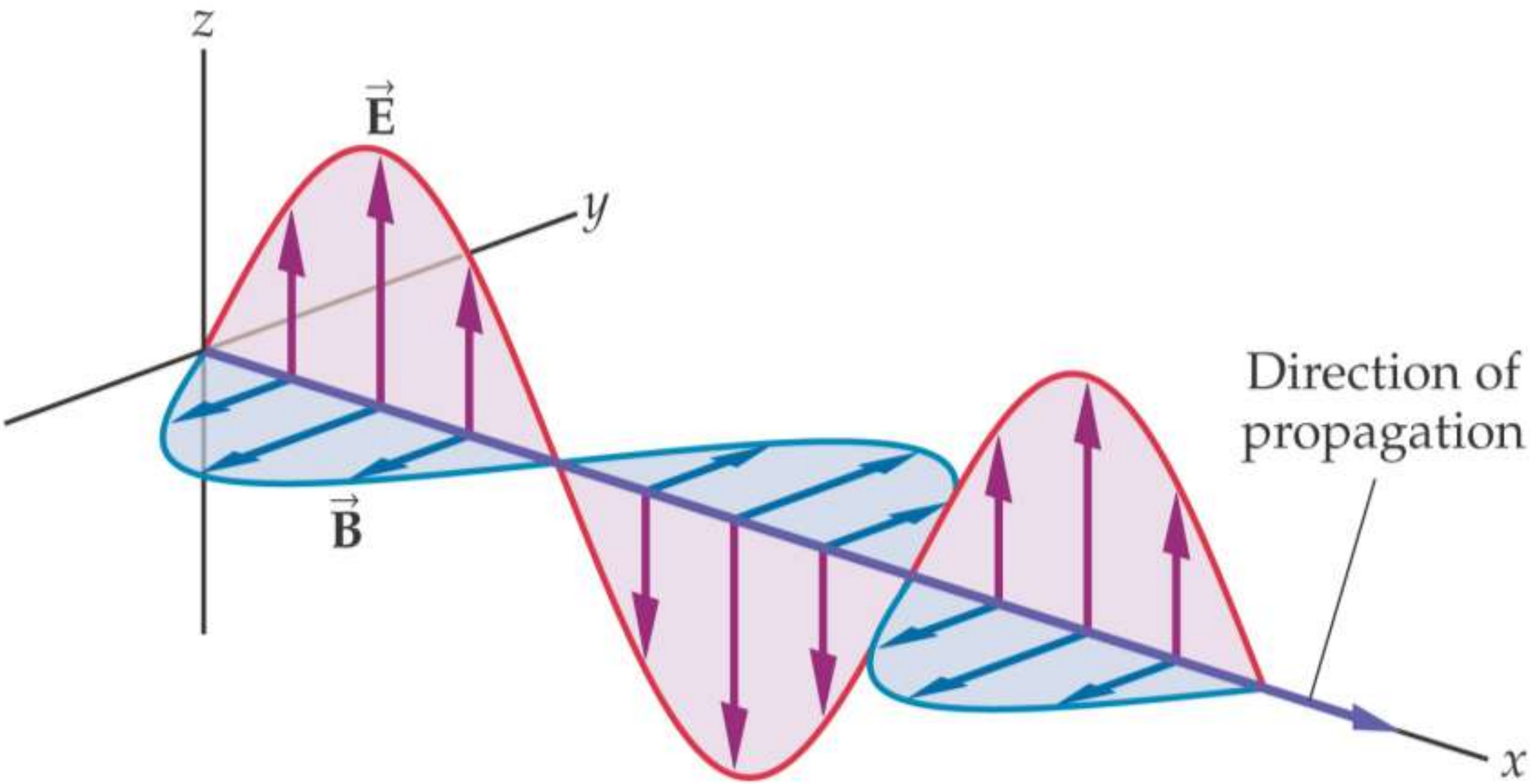
25-1 The Production of Electromagnetic Waves

The previous image showed the electric field; a magnetic field is also generated, perpendicular both to the electric field and to the direction of propagation.

The electric field produced by an antenna connected to an ac generator propagates away from the antenna, analogous to a wave on a string moving away from your hand as you wiggle it up and down.

25-1 The Production of Electromagnetic Waves

An electromagnetic wave propagating in the positive *x* direction, showing the electric and magnetic fields:



25-1 The Production of Electromagnetic Waves

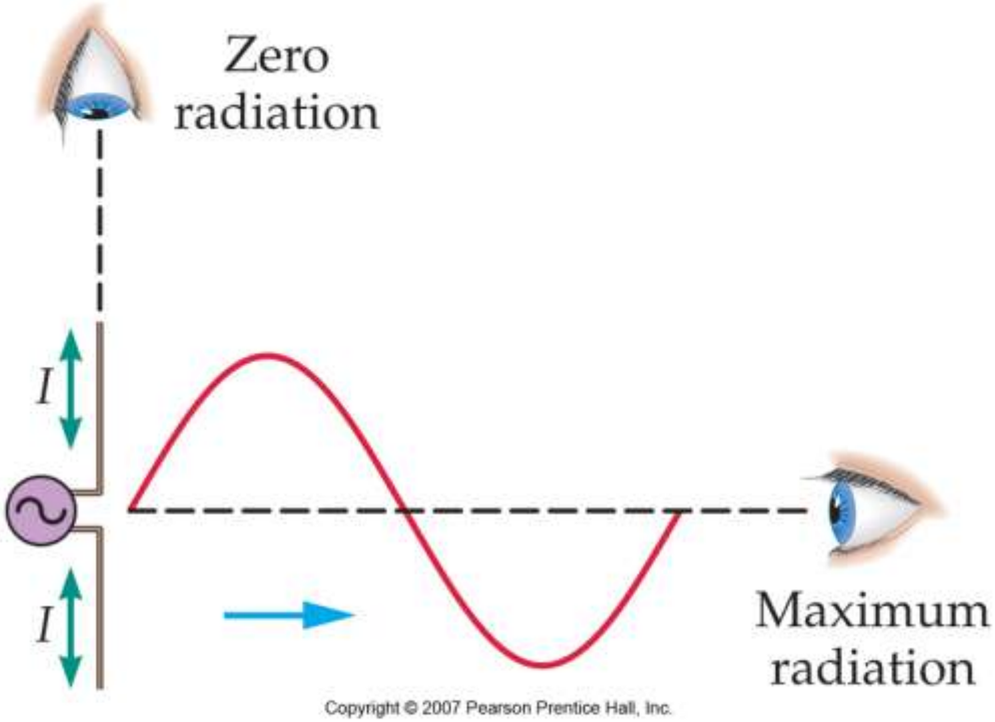
The direction of propagation and the directions of the electric and magnetic fields in an electromagnetic wave can be determined using a right-hand rule:

Point the fingers of your right hand in the direction of E, curl your fingers toward B, and your thumb will point in the direction of propagation.

25-1 The Production of Electromagnetic Waves

Any time an electric charge is accelerated, it will radiate:

Accelerated charges radiate electromagnetic waves.



25-2 The Propagation of Electromagnetic Waves

All electromagnetic waves propagate through a vacuum at the same rate:

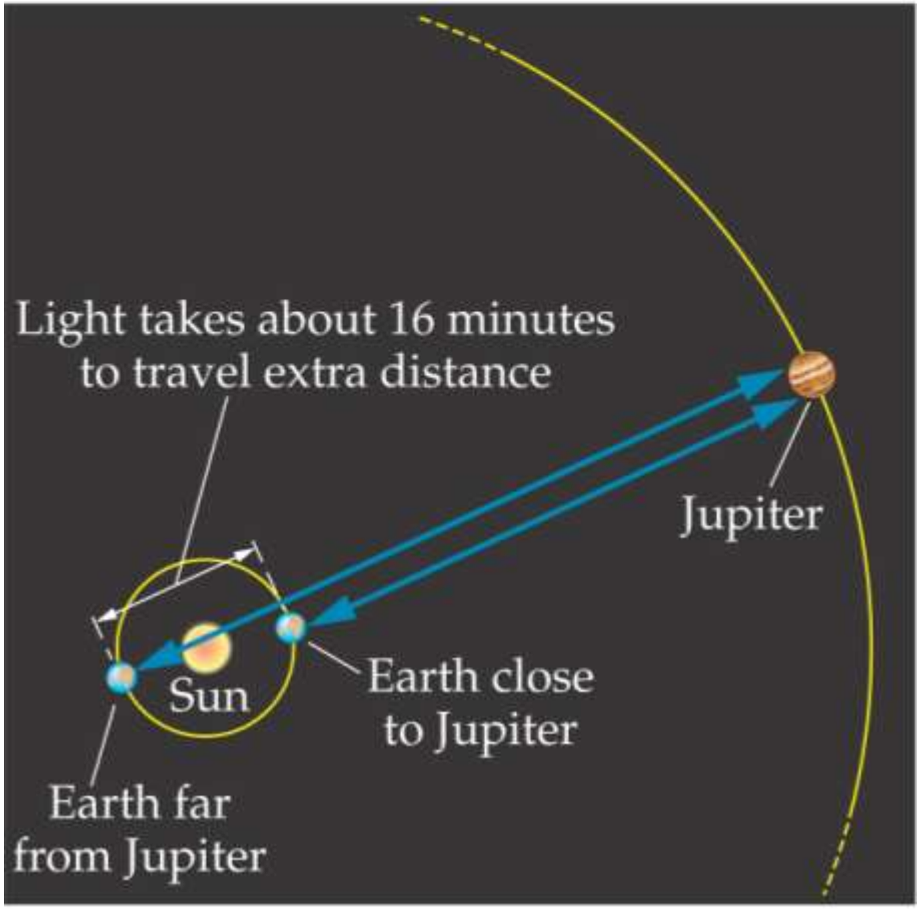
Speed of Light in a Vacuum

$$c = 3.00 \times 10^8 \text{ m/s}$$

In materials, such as air and water, light slows down, but at most to about half the above speed.

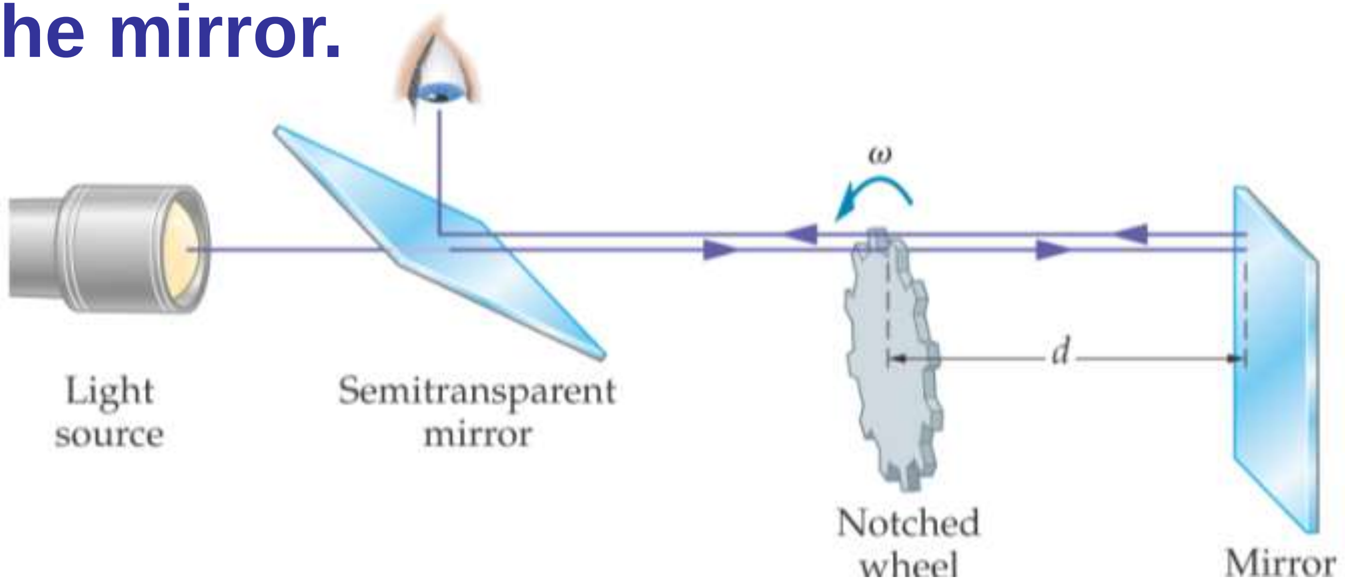
25-2 The Propagation of Electromagnetic Waves

This speed is so large that it is very hard to measure; the first measurements were done in the late 1600s, using the eclipses of the moons of Jupiter.



25-2 The Propagation of Electromagnetic Waves

The first laboratory measurement of the speed of light was done by Fizeau in the latter part of the 19th century. He used a ray of light passing (or not) through a notched mirror, and was able to derive the speed of light from the rotational speed of the mirror and the distance from the wheel to the mirror.



25-2 The Propagation of Electromagnetic Waves

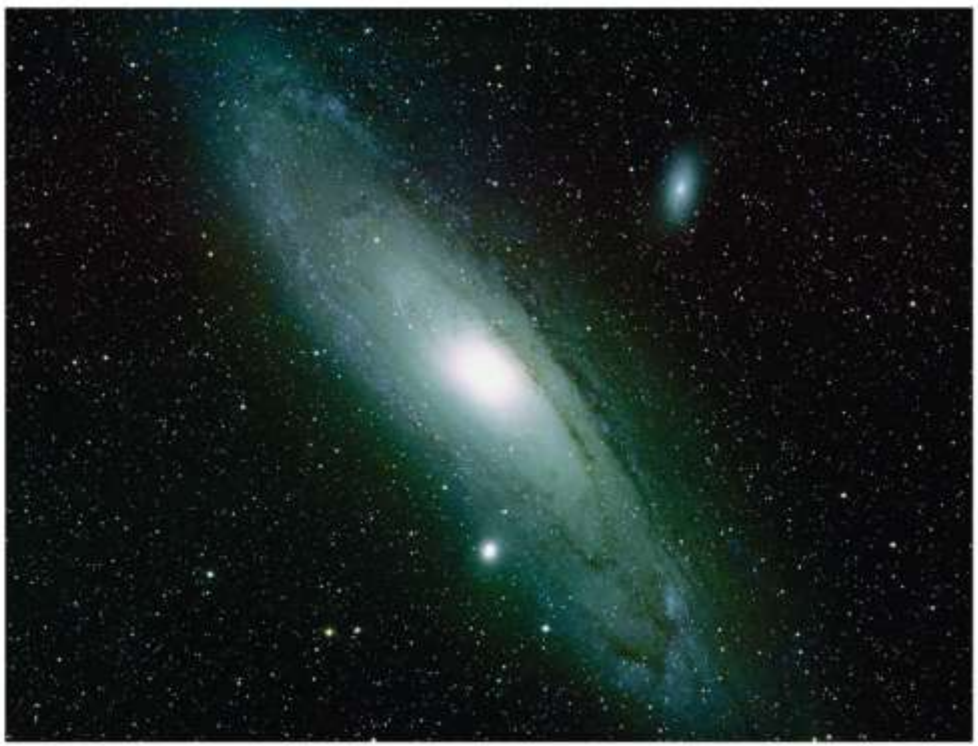
The value of the speed of light is given by electromagnetic theory; it is:

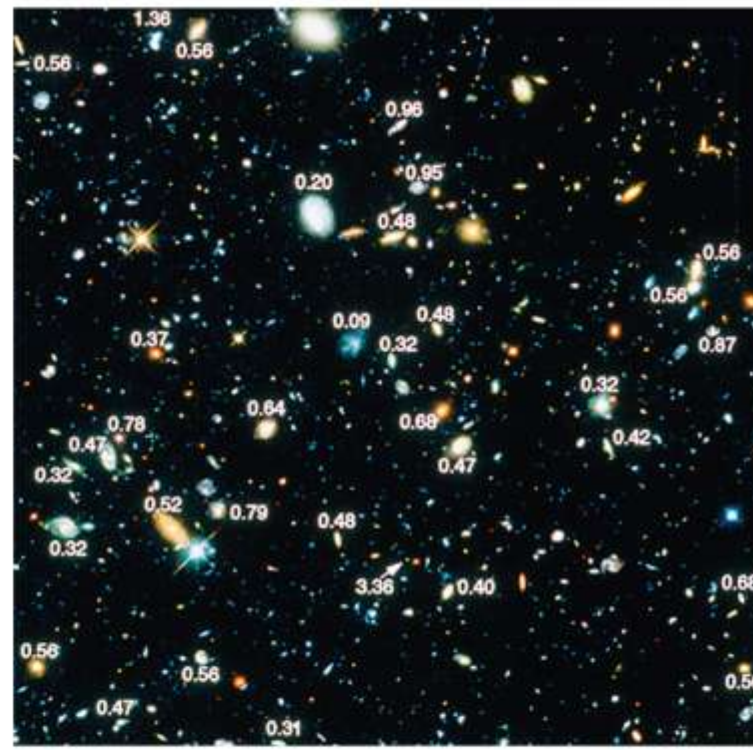
$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

This is a very large speed, but on an astronomical scale, it can take light a long time to travel from one star to another. Astronomical distances are often measured in light-years – the distance light travels in a year.

25-2 The Propagation of Electromagnetic Waves

Light from the Andromeda Galaxy, left, takes about 2 million years to reach us. From the most distant galaxies in the Hubble Deep Field image, right, it takes 13 billion years.



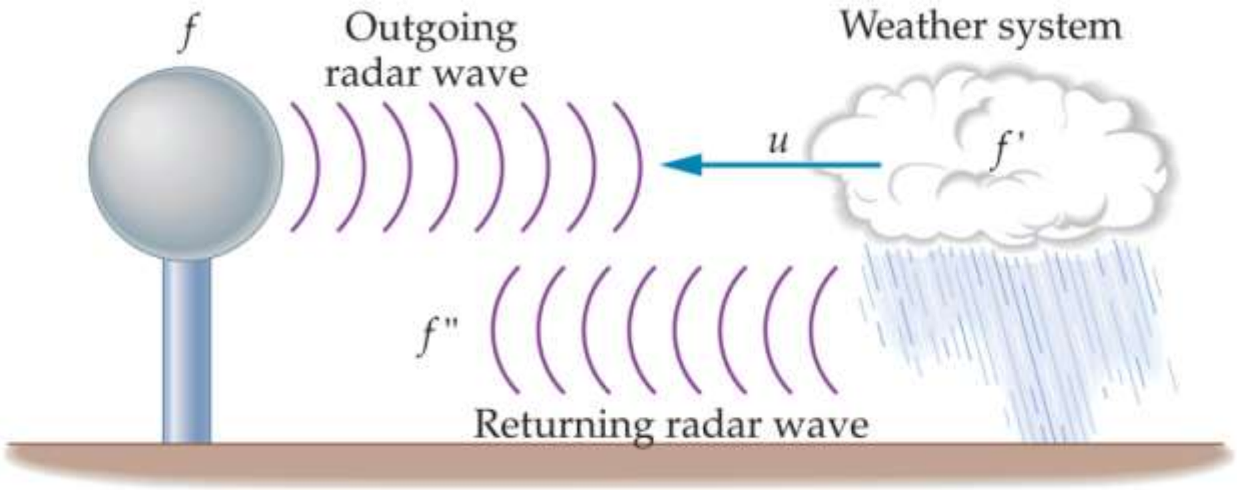


25-2 The Propagation of Electromagnetic Waves

The Doppler effect applies to electromagnetic waves as well as to sound waves.

The speed of the waves in vacuum does not change, but as the observer and source move with respect to one another, the frequency does change.

$$f' = f\left(1 \pm \frac{u}{c}\right)$$

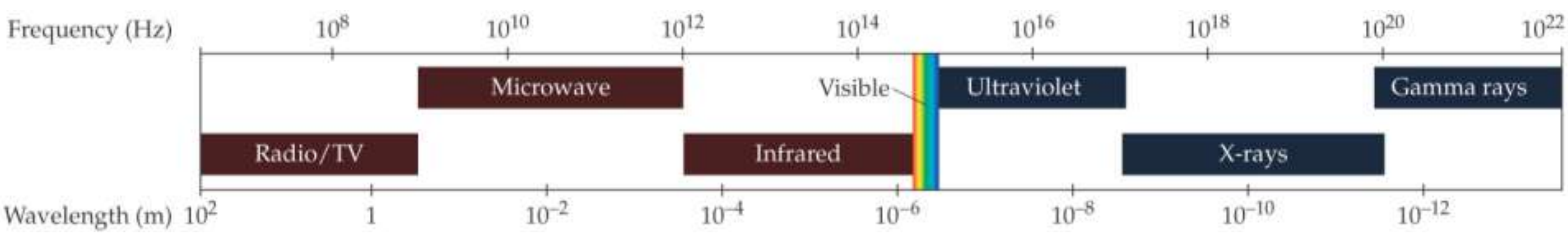


25-3 The Electromagnetic Spectrum

Because all electromagnetic waves have the same speed in vacuum, the relationship between the wavelength and the frequency is simple:

$$c = f\lambda$$

The full range of frequencies of electromagnetic waves is called the electromagnetic spectrum.



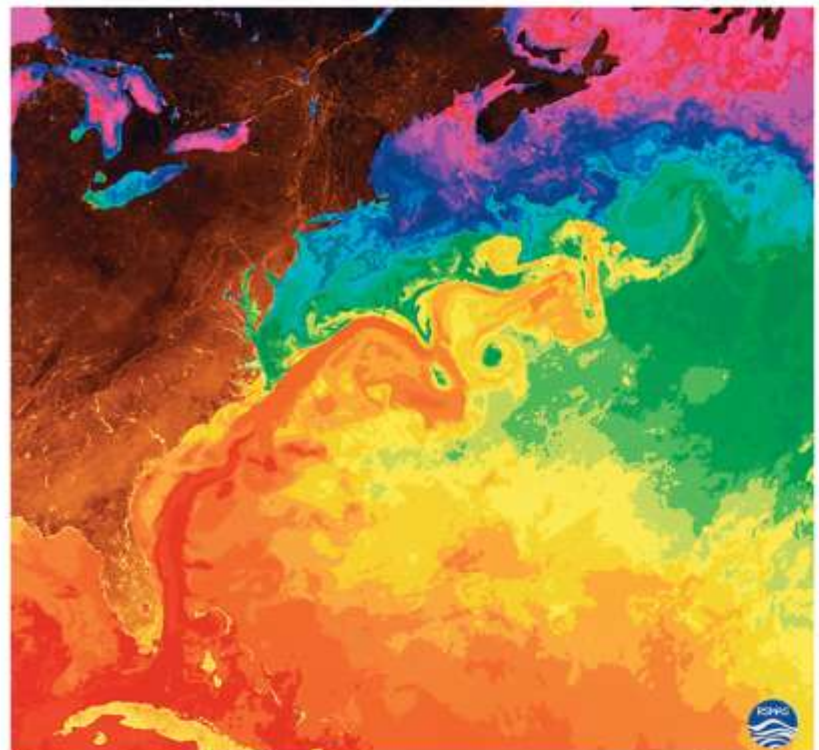
25-3 The Electromagnetic Spectrum

Radio waves are the lowest-frequency electromagnetic waves that we find useful. Radio and television broadcasts are in the range of 10^6 Hz to 10^9 Hz.

Microwaves are used for cooking and also for telecommunications. Microwave frequencies are from 10^9 Hz to 10^{12} Hz, with wavelengths from 1 mm to 30 cm.

25-3 The Electromagnetic Spectrum

Infrared waves are felt as heat by humans. Remote controls operate using infrared radiation. The frequencies are from 10^{12} Hz to 4.3×10^{14} Hz.



25-3 The Electromagnetic Spectrum

Visible light has a fairly narrow frequency range, from 4.3×10^{14} Hz (red) to 7.5×10^{14} Hz (violet).

Ultraviolet light starts with frequencies just above those of visible light, from 7.5×10^{14} Hz to 10^{17} Hz. These rays cause tanning, burning, and skin cancer. Some insects can see in the ultraviolet, and some flowers have special markings that are only visible under ultraviolet light.

X-rays have higher frequencies still, from 10^{17} Hz to 10^{20} Hz. They are used for medical imaging.

25-3 The Electromagnetic Spectrum

Gamma rays have the highest frequencies of all, above 10^{20} Hz. These rays are extremely energetic, and are produced in nuclear reactions. They are destructive to living cells and are therefore used to destroy cancer cells and to sterilize food.

25-4 Energy and Momentum in Electromagnetic Waves

The energy density in an electric field is:

$$u_E = \frac{1}{2}\varepsilon_0 E^2$$

And in a magnetic field:

$$u_B = \frac{1}{2\mu_0}B^2$$

Therefore, the total energy density of an electromagnetic wave is:

$$u = u_E + u_B = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2$$

25-4 Energy and Momentum in Electromagnetic Waves

It can be shown that the energy densities in the electric and magnetic fields are equal:

$$u_{\mathrm{av}} = \tfrac{1}{2}\varepsilon_0 E_{\mathrm{rms}}{}^2 + \frac{1}{2\mu_0} B_{\mathrm{rms}}{}^2 = \varepsilon_0 E_{\mathrm{rms}}{}^2 = \frac{1}{\mu_0} B_{\mathrm{rms}}{}^2$$

Therefore:

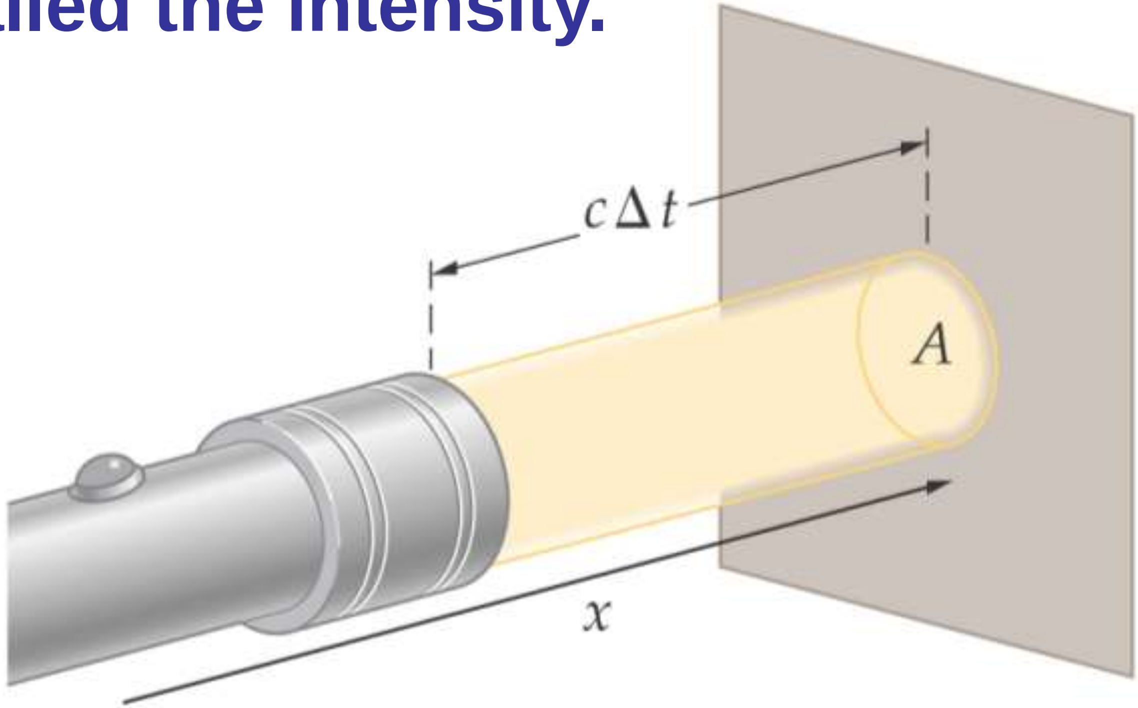
$$\tfrac{1}{2}\varepsilon_0 E^2 = \frac{1}{2\mu_0} B^2$$

$$E = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} B$$

$$= cB$$

25-4 Energy and Momentum in Electromagnetic Waves

The energy a wave delivers to a unit area in a unit time is called the intensity.



$$I = \frac{\Delta U}{A\Delta t} = \frac{u(Ac\Delta t)}{A\Delta t} = uc$$

25-4 Energy and Momentum in Electromagnetic Waves

Substituting for the energy density,

$$I = uc = \frac{1}{2}c\varepsilon_0 E^2 + \frac{1}{2\mu_0}cB^2 = c\varepsilon_0 E^2 = \frac{c}{\mu_0}B^2$$

An electromagnetic wave also carries momentum:

$$p = \frac{U}{c}$$

25-4 Energy and Momentum in Electromagnetic Waves

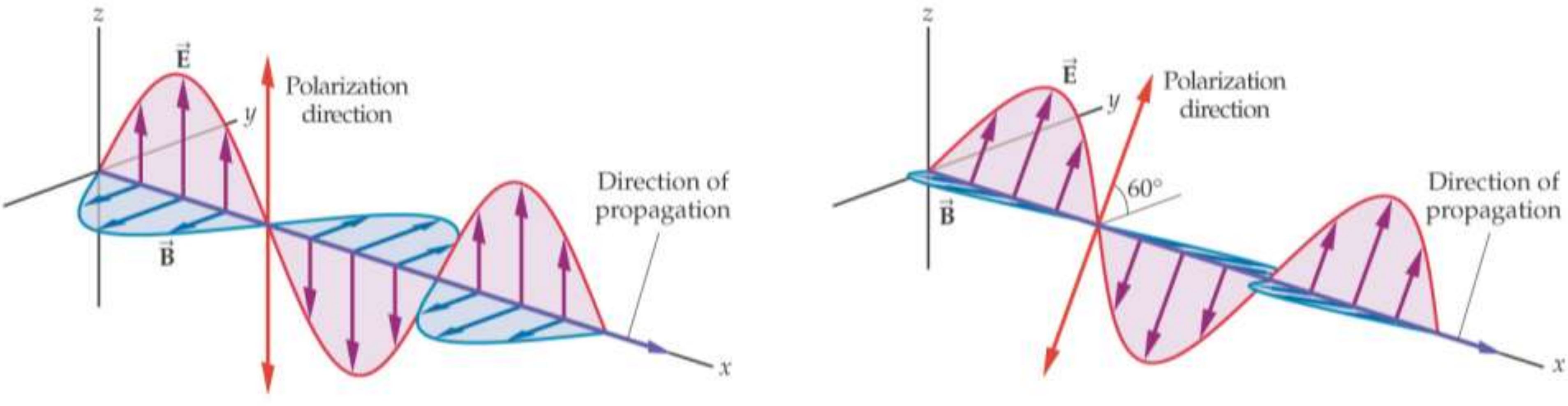
Therefore, it exerts pressure, called the radiation pressure:

$$\text{pressure}_{\text{av}} = \frac{I_{\text{av}}}{c}$$

Radiation pressure is responsible for the curvature of this comet's dust tail.

25-5 Polarization

The polarization of an electromagnetic wave refers to the direction of its electric field.

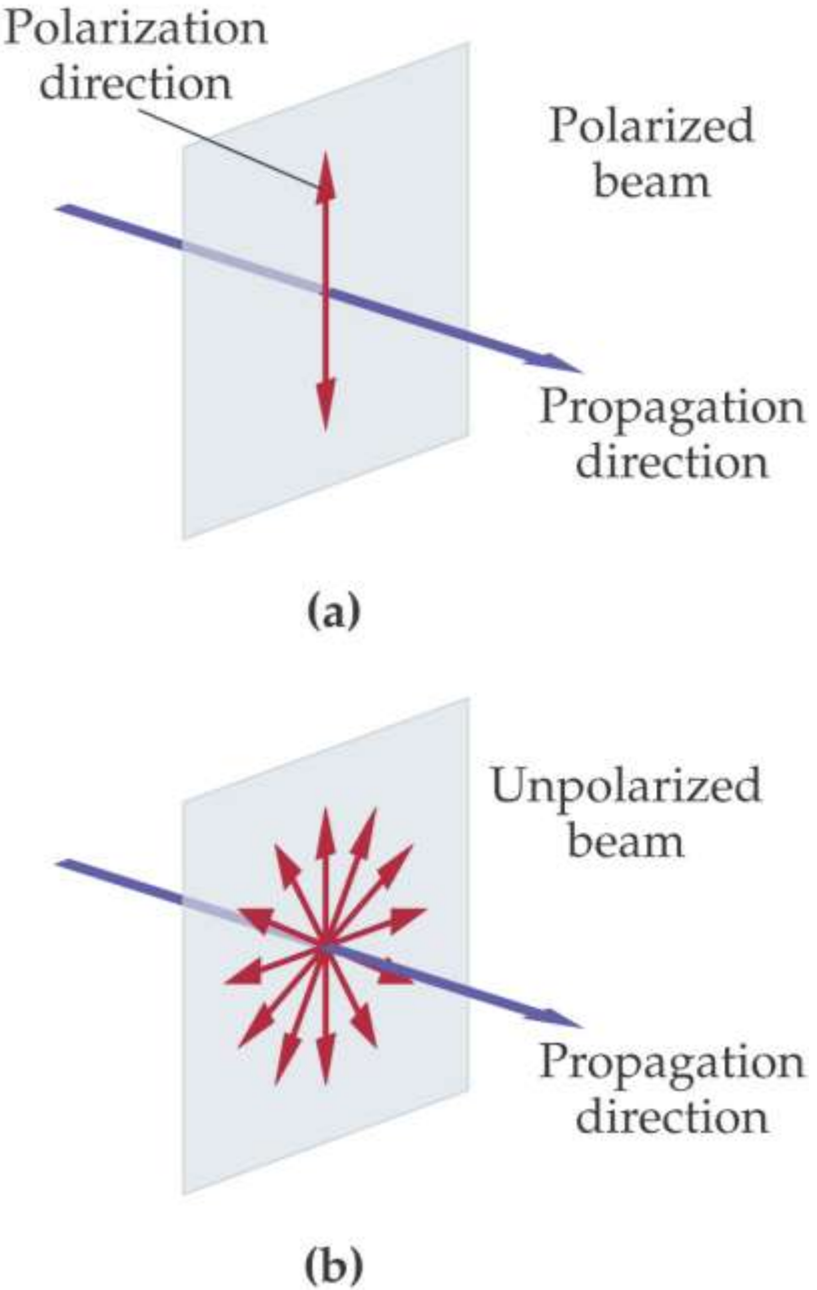


(a) (b)

25-5 Polarization

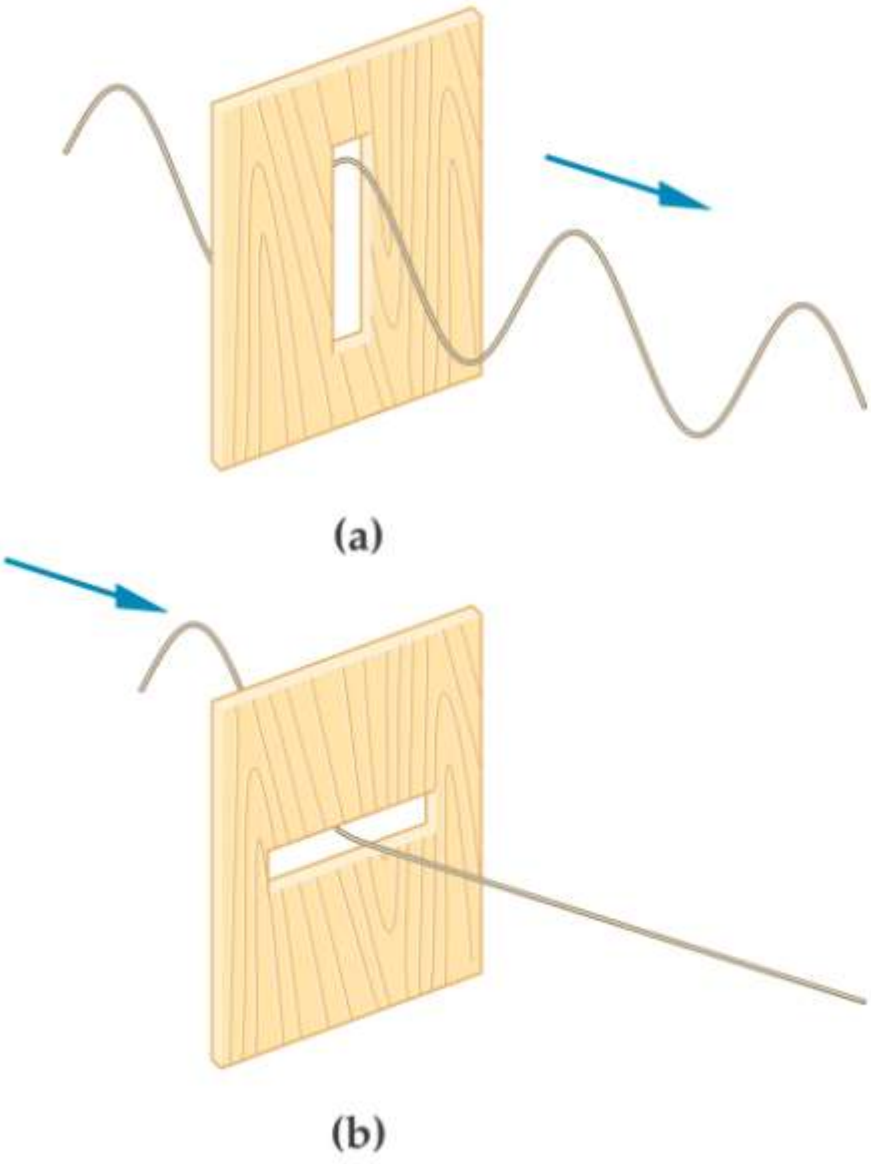
Polarized light has its electric fields all in the same direction.

Unpolarized light has its electric fields in random directions.



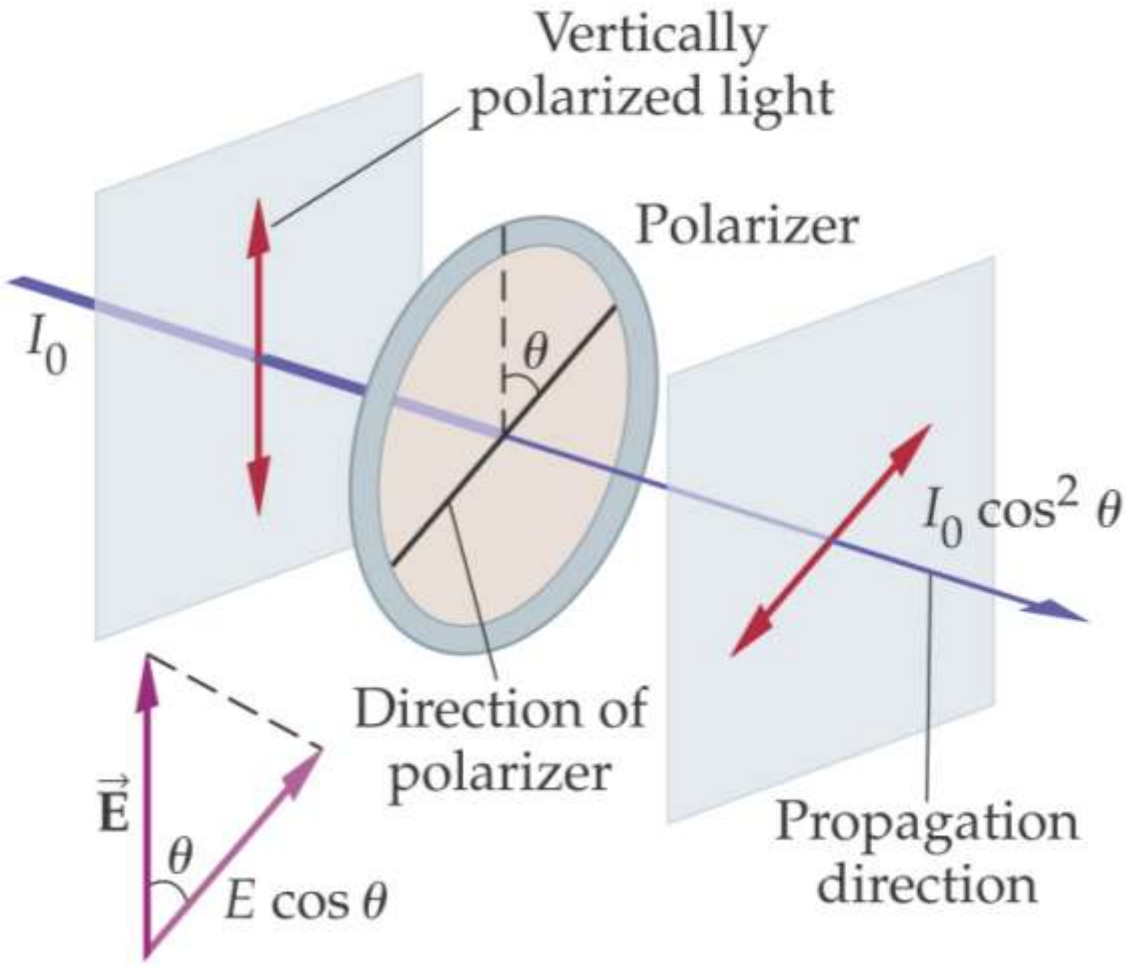
25-5 Polarization

A beam of unpolarized light can be polarized by passing it through a polarizer, which allows only a particular component of the electric field to pass through. Here is a mechanical analog:



25-5 Polarization

A polarizer will transmit the component of light in the polarization direction:



25-5 Polarization

Since the intensity of light is proportional to the square of the field, the intensity of the transmitted beam is given by the Law of Malus:

Law of Malus

$$I = I_0 \cos^2 \theta$$

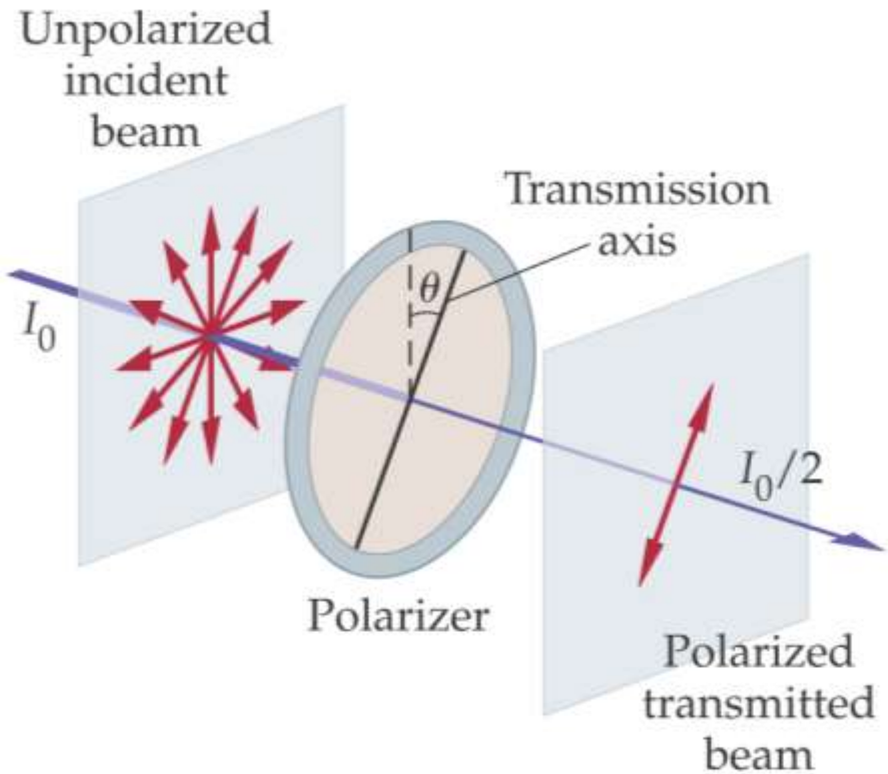
The light exiting from a polarizer is polarized in the direction of the polarizer.

25-5 Polarization

If an unpolarized beam is passed through a polarizer, the transmitted intensity is half the initial intensity.

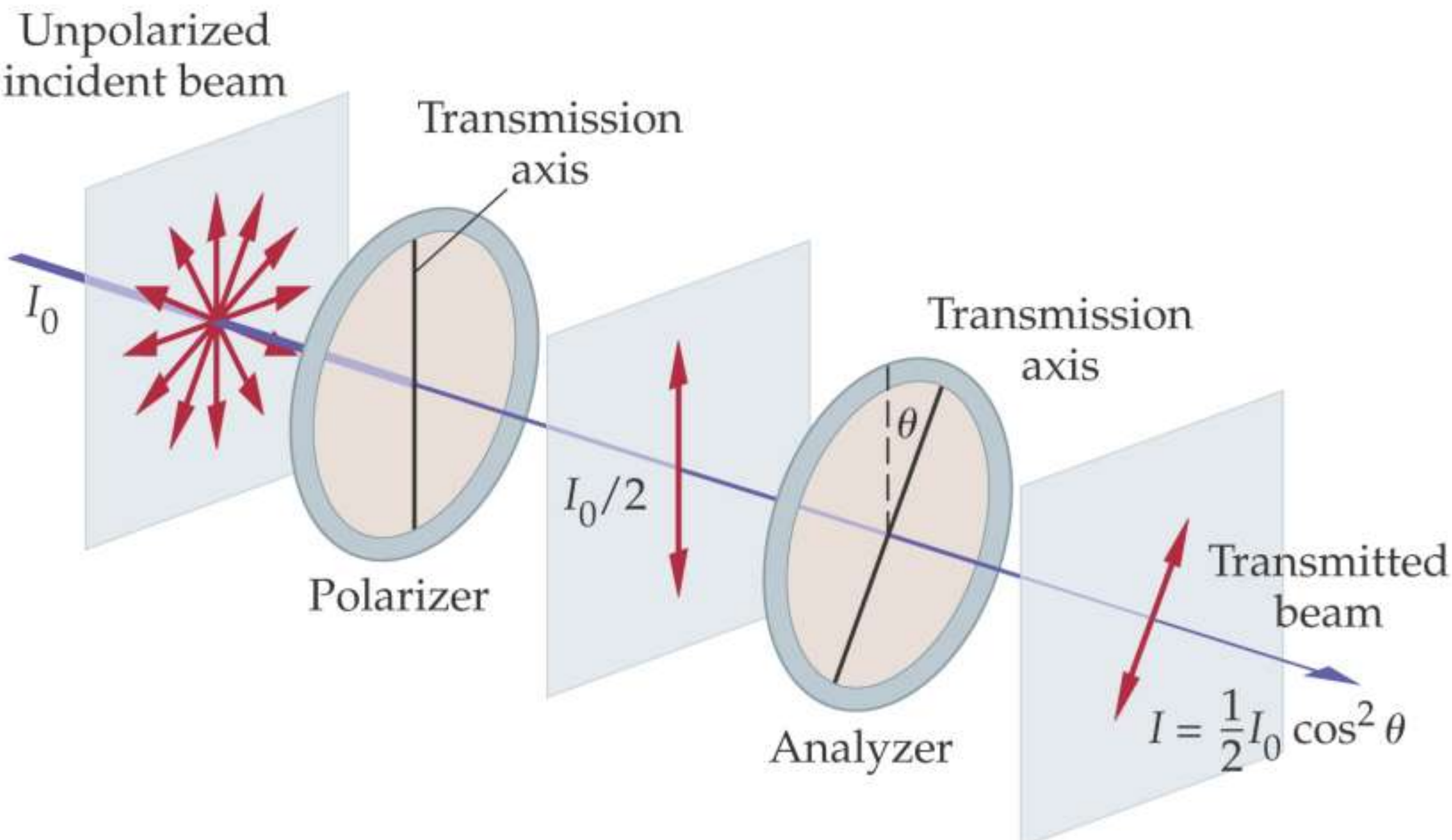
Transmitted Intensity for an Unpolarized Beam

$$I = \frac{1}{2} I_0$$

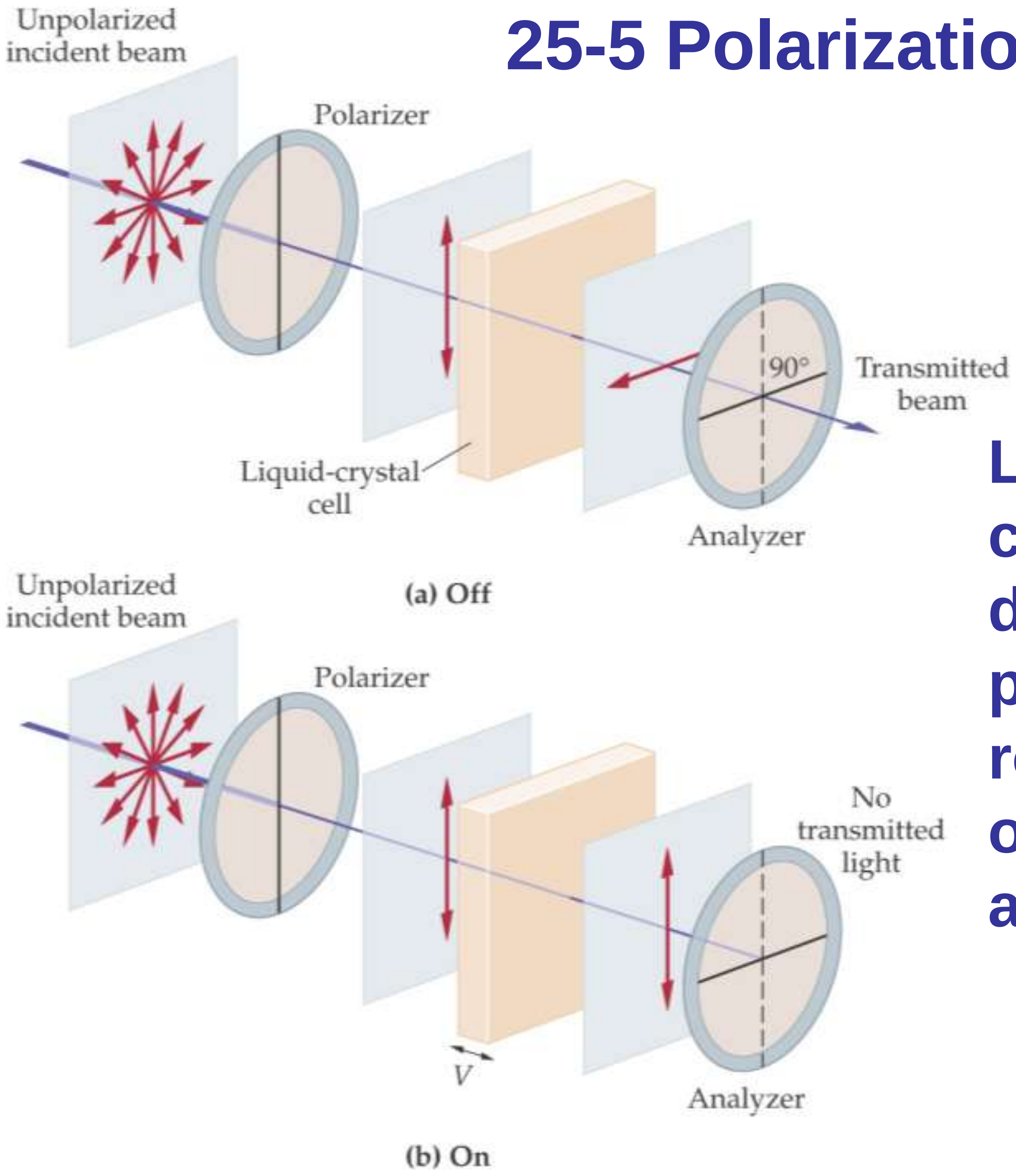


25-5 Polarization

A polarizer and an analyzer can be combined; the final intensity is: $I = \frac{1}{2} I_0 \cos^2 \theta$



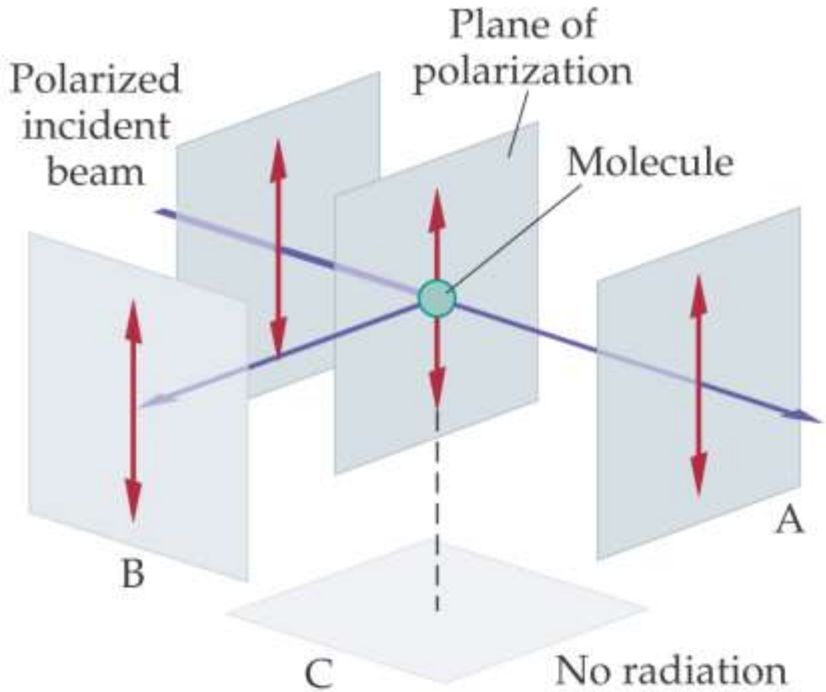
25-5 Polarization

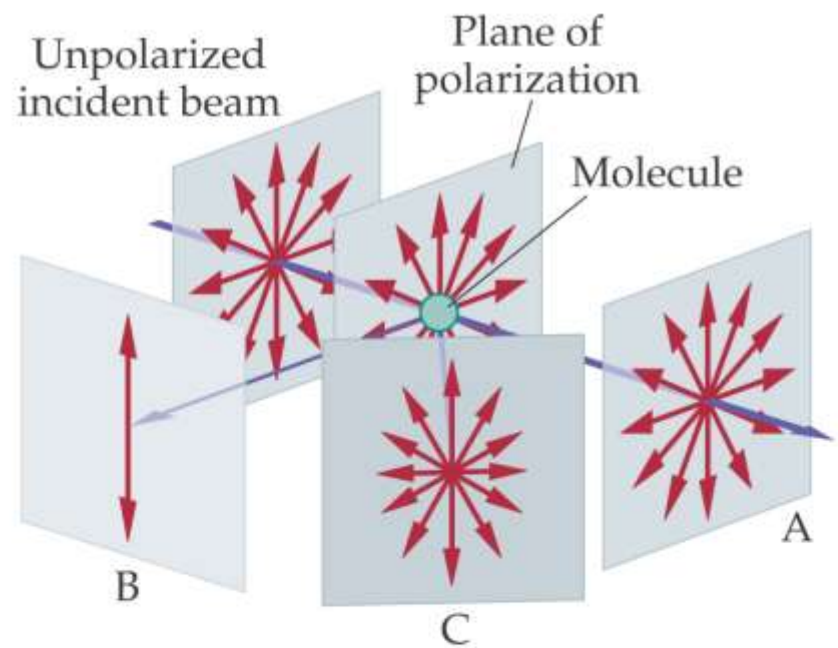


LCDs use liquid crystals, whose direction of polarization can be rotated depending on the voltage across them.

25-5 Polarization

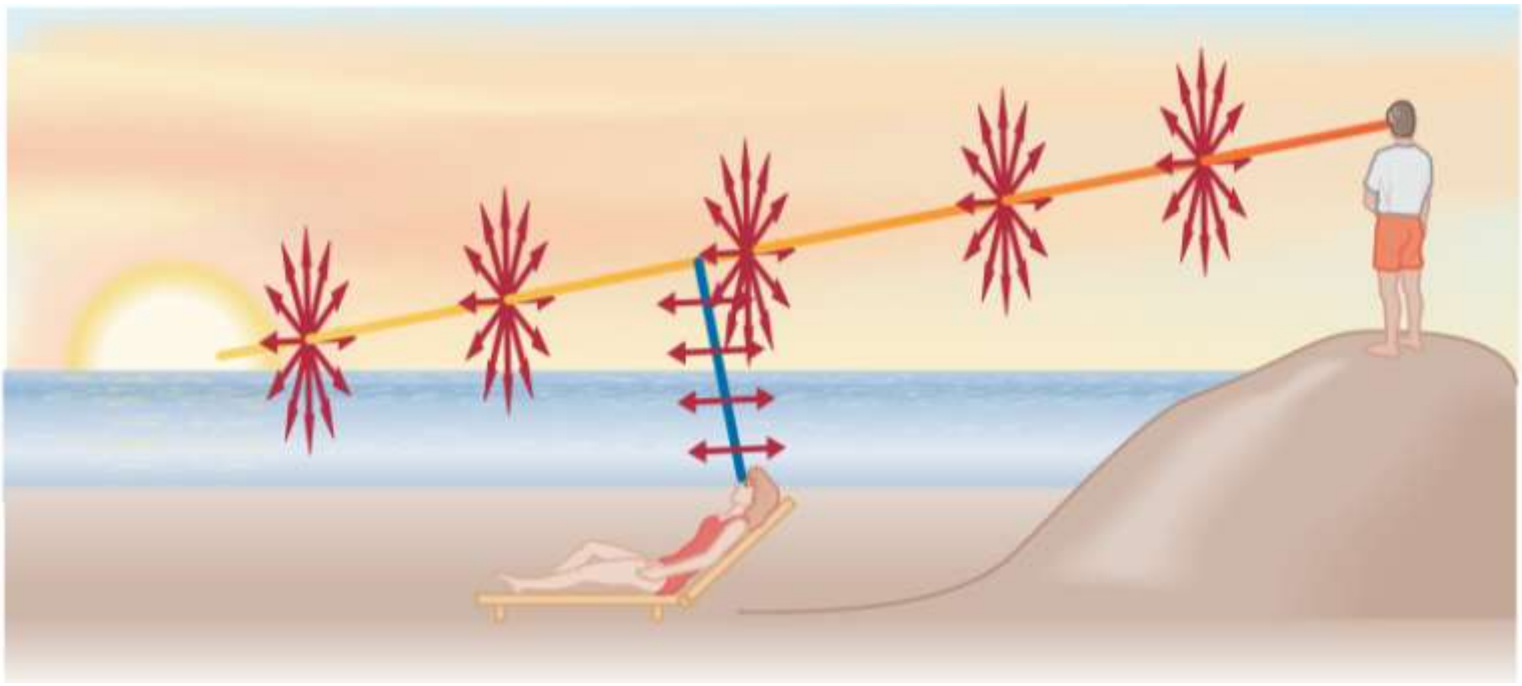
Unpolarized light can be partially or completely polarized by scattering from atoms or molecules, which act as small antennas. If the light is already polarized, its transmission will depend on its polarization.





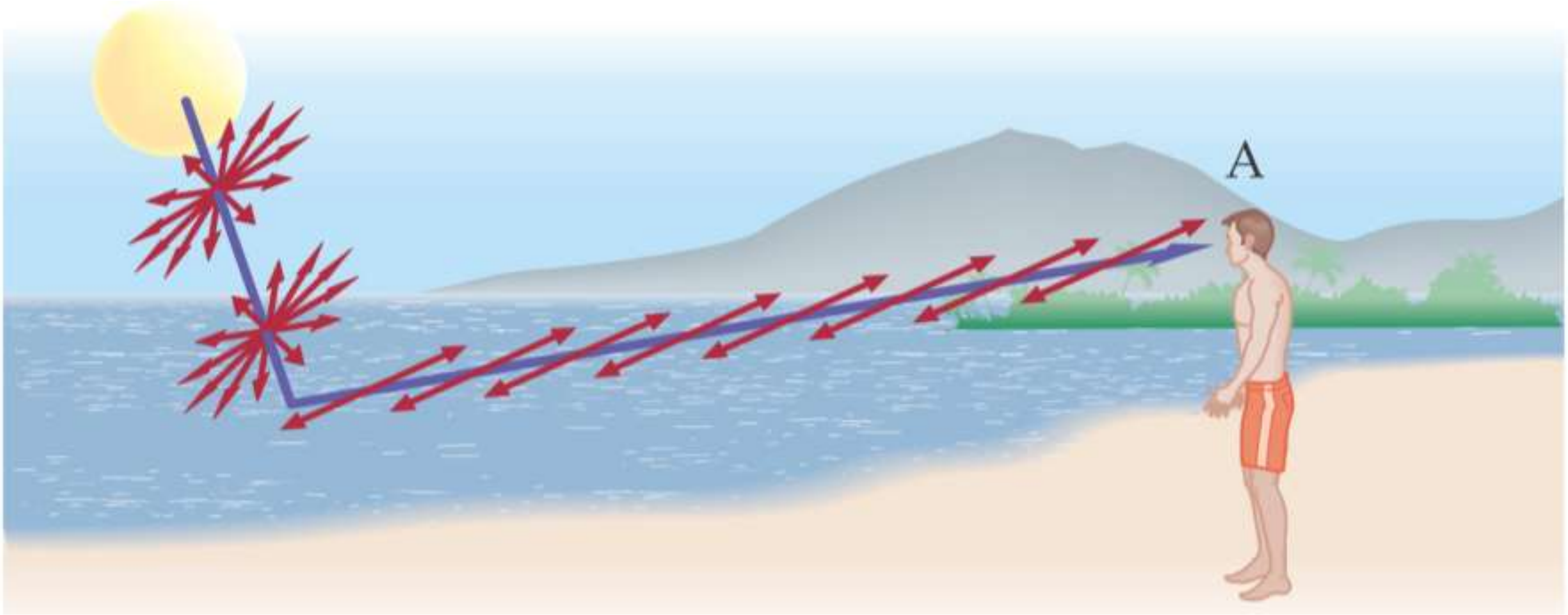
25-5 Polarization

This means that sunlight will be polarized, depending on the angle our line of sight makes with the direction to the Sun.



25-5 Polarization

Polarization can also occur when light reflects from a smooth surface:



Summary of Chapter 25

- Electromagnetic waves are traveling waves of oscillating electric and magnetic fields.
- Electric and magnetic fields in an electromagnetic wave are perpendicular to each other and to the direction of propagation, and are in phase.
- A right-hand rule gives the directions of the fields and propagation.
- Any accelerated charge will emit electromagnetic waves.

Summary of Chapter 25

- **Electromagnetic waves can travel through a vacuum; their speed in a vacuum is always the same:**

$$c = 3.00 \times 10^8 \text{ m/s}$$

- **Doppler effect:**

$$f' = f\left(1 \pm \frac{u}{c}\right)$$

- **Electromagnetic waves can have any frequency.**

Summary of Chapter 25

- **The entire range of frequencies is called the electromagnetic spectrum. Named portions of the spectrum, from the lowest frequencies to the highest, are radio waves; microwaves; infrared; visible light; ultraviolet; X-rays; and gamma rays.**

- **Relationship of frequency and wavelength:**

$$c = f\lambda$$

- **Energy density of an electromagnetic wave:**

$$u = \tfrac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2 = \varepsilon_0 E^2 = \frac{1}{\mu_0}B^2$$

Summary of Chapter 25

- **Relationship of E and B fields:** $E = cB$

- **Intensity of an electromagnetic wave:**

$$I = uc = \tfrac{1}{2}c\varepsilon_0 E^2 + \frac{1}{2\mu_0}cB^2 = c\varepsilon_0 E^2 = \frac{c}{\mu_0}B^2$$

- **Momentum of an electromagnetic wave (*U* is the energy):**

$$p = \frac{U}{c}$$

- **Radiation pressure:**

$$\text{pressure}_{\text{av}} = \frac{I_{\text{av}}}{c}$$

Summary of Chapter 25

- The polarization of a beam of light is the direction of its electric field.
- A polarizer transmits only light whose electric field has a component along the polarizer's axis.
- An initially polarized beam of light encountering a polarizer at an angle θ has transmitted intensity:

$$I = I_0 \cos^2 \theta$$

Summary of Chapter 25

• Transmitted intensity of an initially unpolarized beam of light:

$$I = \frac{1}{2} I_0$$

• Light scattered from the atmosphere is polarized when viewed at right angles to the Sun.

• When light reflects from a horizontal surface, it is partially polarized in the horizontal direction.