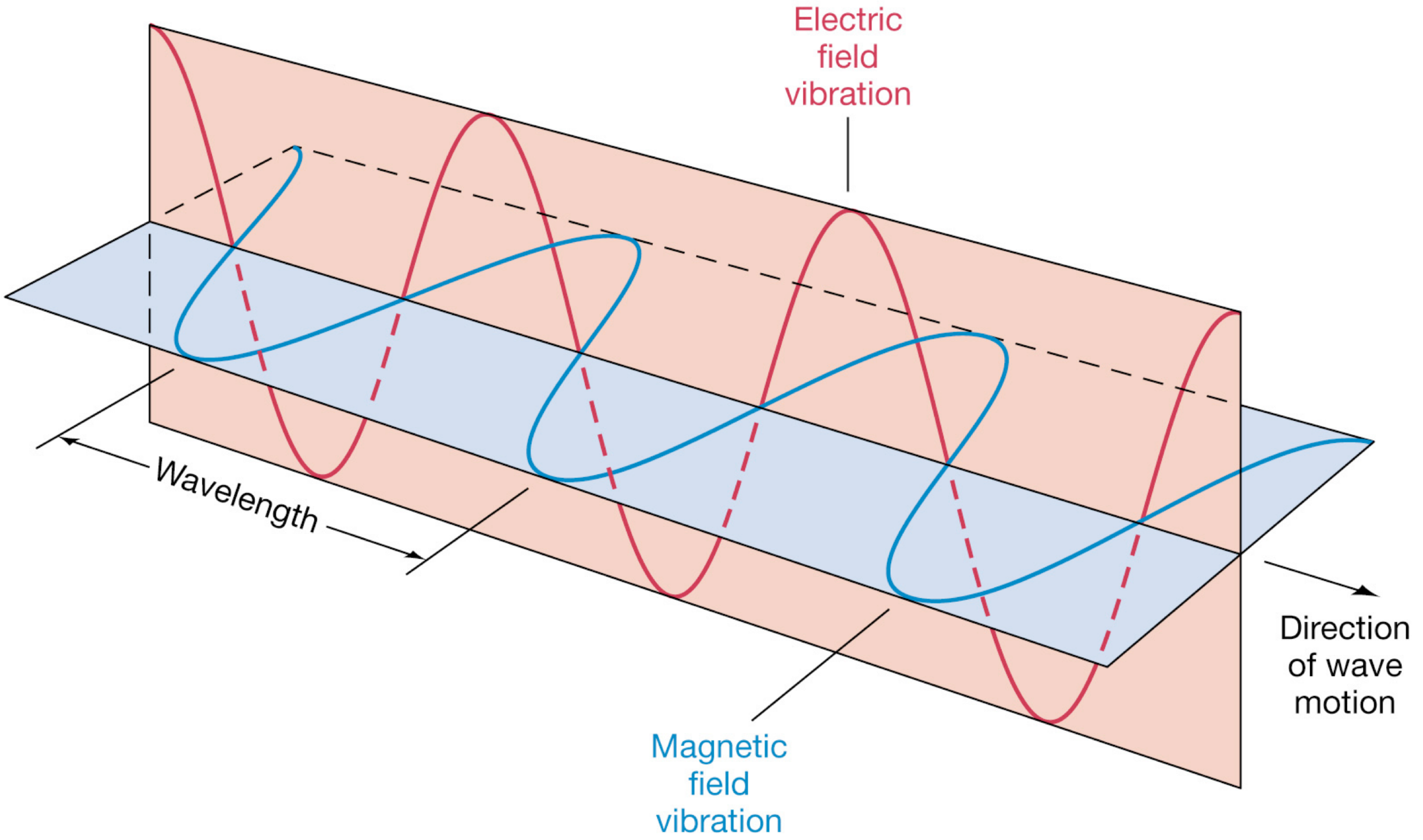
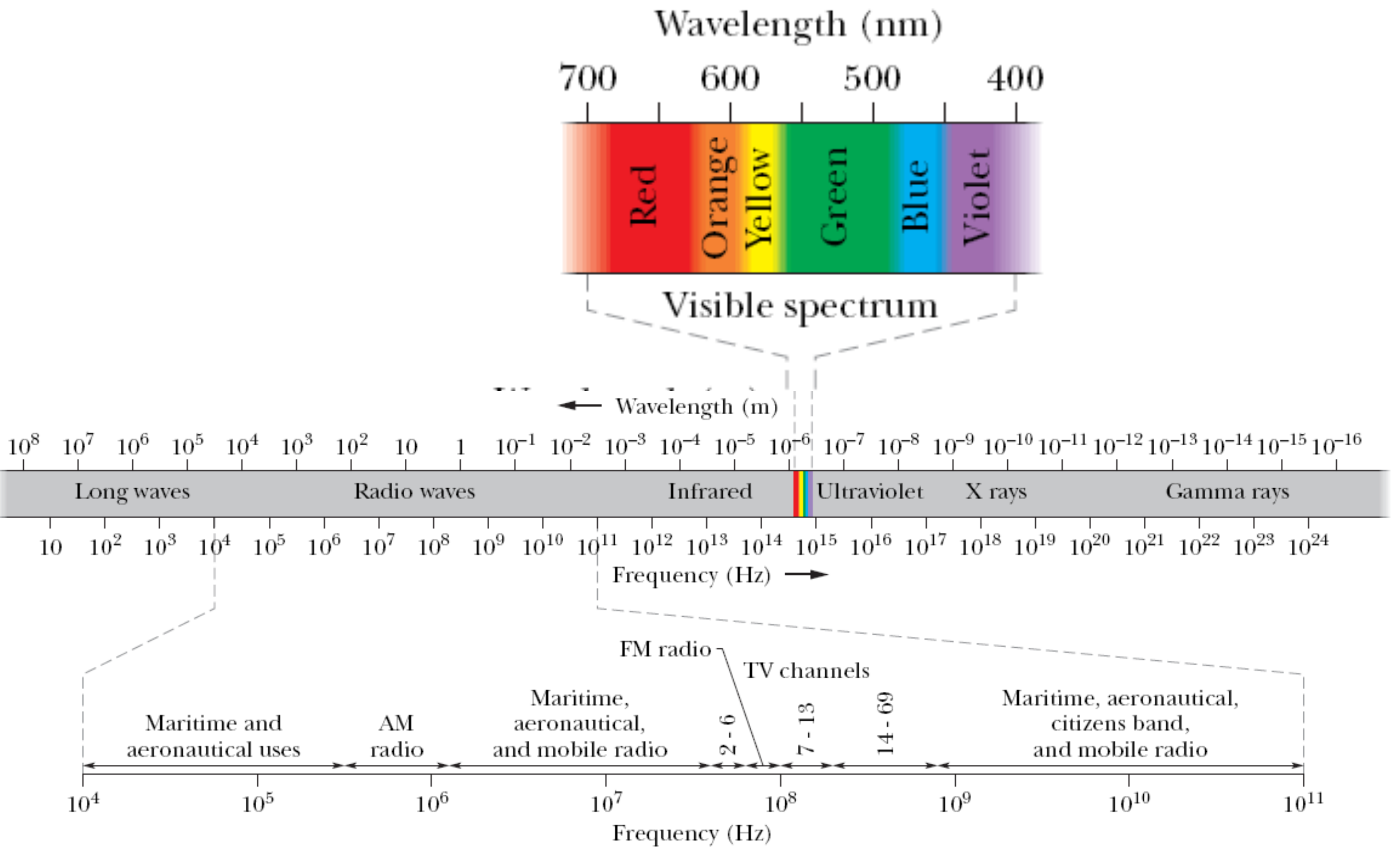
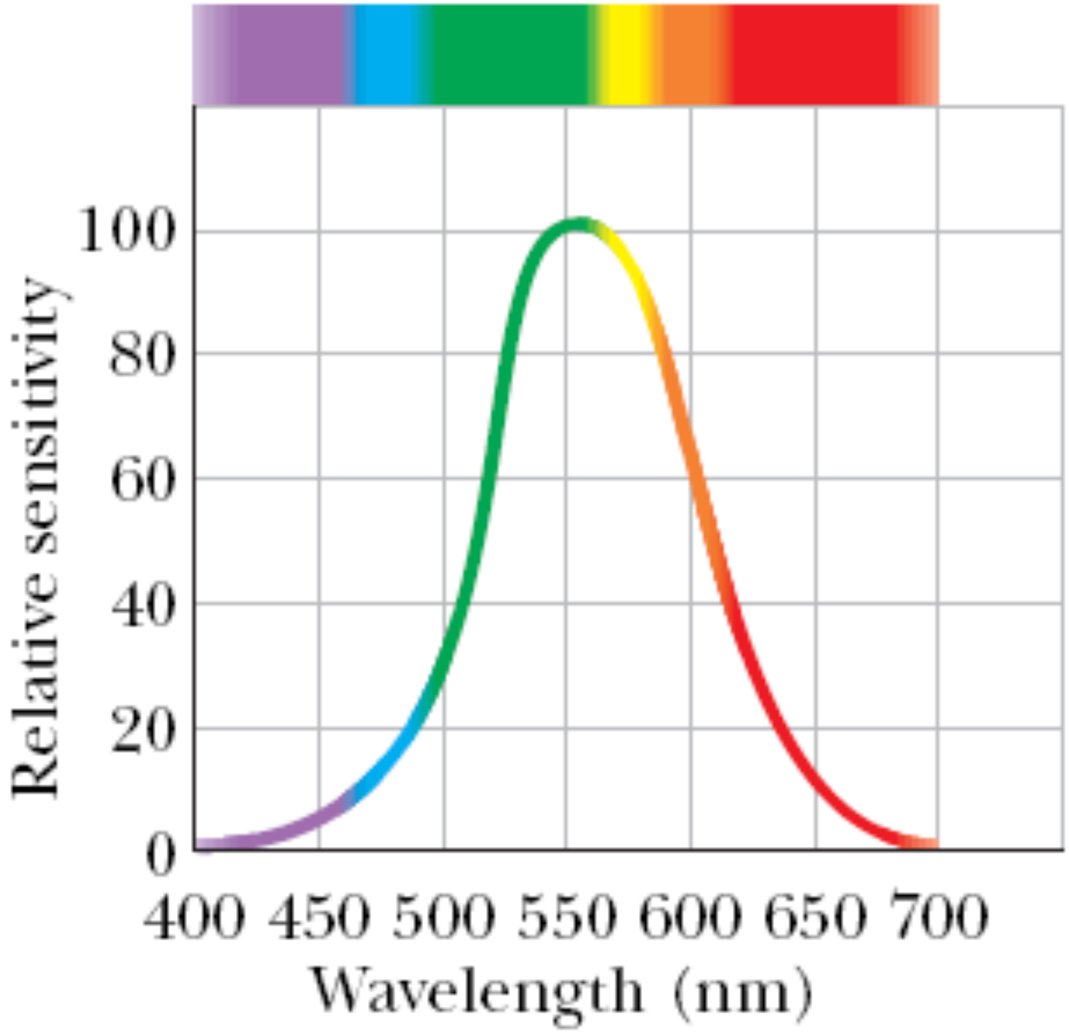
Electromagnetic Waves and Light Propagations



Maxwell's Rainbow



Maxwell’s Rainbow: Visible Spectrum



The Traveling Wave

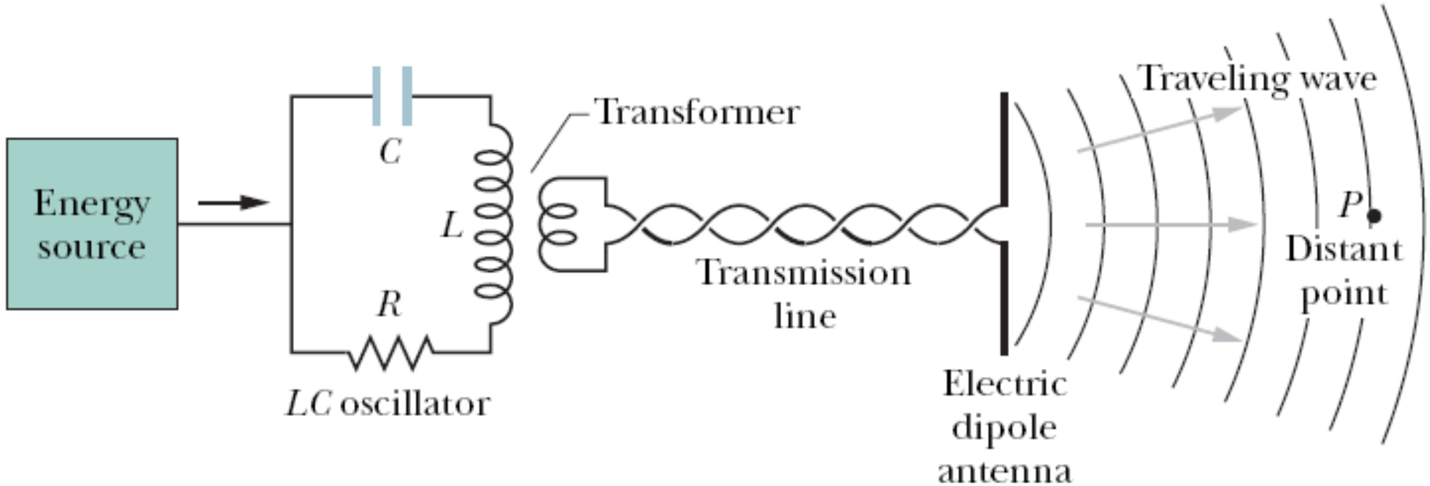


Fig. 33-3 An arrangement for generating a traveling electromagnetic wave in the shortwave radio region of the spectrum: an *LC* oscillator produces a sinusoidal current in the antenna, which generates the wave. *P* is a distant point at which a detector can monitor the wave traveling past it.

Some electromagnetic waves, including x rays, gamma rays, and visible light, are *radiated (emitted)* from sources that are of atomic or nuclear size. Figure 33-3 shows the generation of such waves. At its heart is an *LC oscillator,* which establishes an angular frequency w(=1/√(LC)). Charges and currents in this circuit vary sinusoidally at this frequency.

The Traveling Wave

We can write the electric and magnetic fields as sinusoidal functions of position x (along the path of the wave) and time t :

$$E = E_m \sin(kx - \omega t),$$

$$B = B_m \sin(kx - \omega t),$$

Here E_m and B_m are the amplitudes of the fields and, ω and k are the angular frequency and angular wave number of the wave, respectively.

All electromagnetic waves, including visible light, have the same speed c in vacuum.

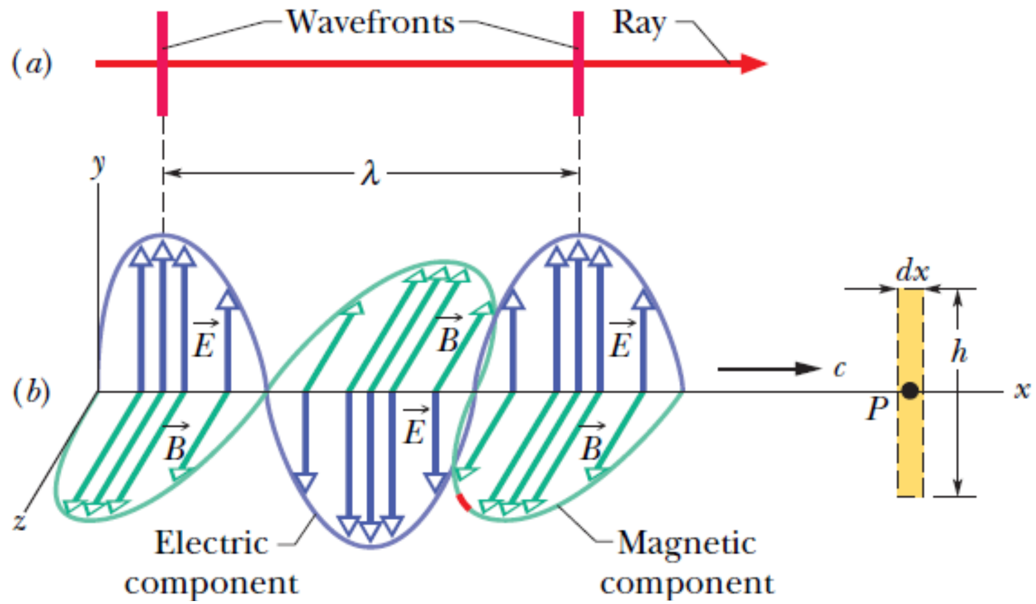
The speed of the wave (in vacuum) is given by c.

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \qquad \text{(wave speed)},$$

Its value is about 3.0 x10^8 m/s.

The Traveling Wave

Exam the magnetic flux through the dashed rectangle of dimensions dx and h fixed at point P on the x axis and in the xy plane.



As the electromagnetic wave moves rightward past the rectangle, the magnetic flux B through the rectangle changes and induces electric fields appear throughout the region of the rectangle. We take **E** and **E + dE** to be the induced fields along the two long sides of the rectangle. These induced electric fields are, in fact, the electrical component of the electromagnetic wave.

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt} = (E + dE)h - Eh = h\,dE.$$

$$\frac{d\Phi_B}{dt} = h\,dx\,\frac{dB}{dt} \Rightarrow h\,dE = -h\,dx\,\frac{dB}{dt} \Rightarrow \frac{dE}{dx} = -\frac{dB}{dt}.$$

$$\frac{\partial E}{\partial x} = kE_m \cos(kx - \omega t)$$

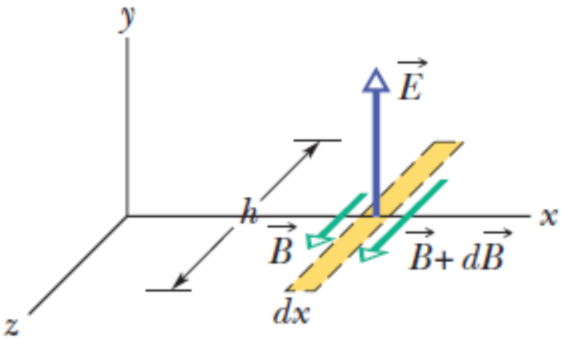
$$\frac{\partial B}{\partial t} = -\omega B_m \cos(kx - \omega t).$$

$$kE_m \cos(kx - \omega t) = \omega B_m \cos(kx - \omega t).$$

$$\boxed{\frac{E_m}{B_m} = c \qquad \text{(amplitude ratio),}}$$

The Traveling Wave

The oscillating electric field induces an oscillating and perpendicular magnetic field.



The sinusoidal variation of the electric field $\boldsymbol{E}$ through the rectangle along the z-axis induces magnetic fields along the rectangle. The instant shown is decreasing in magnitude, and the magnitude of the induced magnetic field is greater on the right side of the rectangle than on the left.

$$\oint \vec{B}\cdot d\vec{s} = \mu_0\varepsilon_0 \frac{d\Phi_E}{dt},$$

$$\oint \vec{B}\cdot d\vec{s} = -(B + dB)h + Bh = -h\,dB.$$

$$\Phi_E = (E)(h\,dx), \qquad \frac{d\Phi_E}{dt} = h\,dx\,\frac{dE}{dt}$$

$$-h\,dB = \mu_0\varepsilon_0\left(h\,dx\,\frac{dE}{dt}\right)$$

$$-\frac{\partial B}{\partial x} = \mu_0\varepsilon_0\frac{\partial E}{\partial t}.$$

$$-kB_m\cos(kx - \omega t) = -\mu_0\varepsilon_0\omega E_m\cos(kx - \omega t),$$

$$\frac{E_m}{B_m} = \frac{1}{\mu_0\varepsilon_0(\omega/k)} = \frac{1}{\mu_0\varepsilon_0 c}.$$

$$\boxed{c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \qquad \text{(wave speed)},}$$

Energy Transport and the Poynting Vector

The direction of the Poynting vector $\vec{S}$ of an electromagnetic wave at any point gives the wave's direction of travel and the direction of energy transport at that point.

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B} \qquad \text{(Poynting vector).}$$

$$S = \left(\frac{\text{energy/time}}{\text{area}}\right)_{\text{inst}} = \left(\frac{\text{power}}{\text{area}}\right)_{\text{inst}}.$$

$$S = \frac{1}{\mu_0}EB, \quad \Rightarrow \quad S = \frac{1}{c\mu_0}E^2$$

$$I = S_{\text{avg}} = \left(\frac{\text{energy/time}}{\text{area}}\right)_{\text{avg}} = \left(\frac{\text{power}}{\text{area}}\right)_{\text{avg}} = \frac{1}{c\mu_0}[E^2]_{\text{avg}} = \frac{1}{c\mu_0}[E_m^2 \sin^2(kx - \omega t)]_{\text{avg}}.$$

$$E_{\text{rms}} = \frac{E_m}{\sqrt{2}}. \quad \Rightarrow \quad I = \frac{1}{c\mu_0}E_{\text{rms}}^2.$$

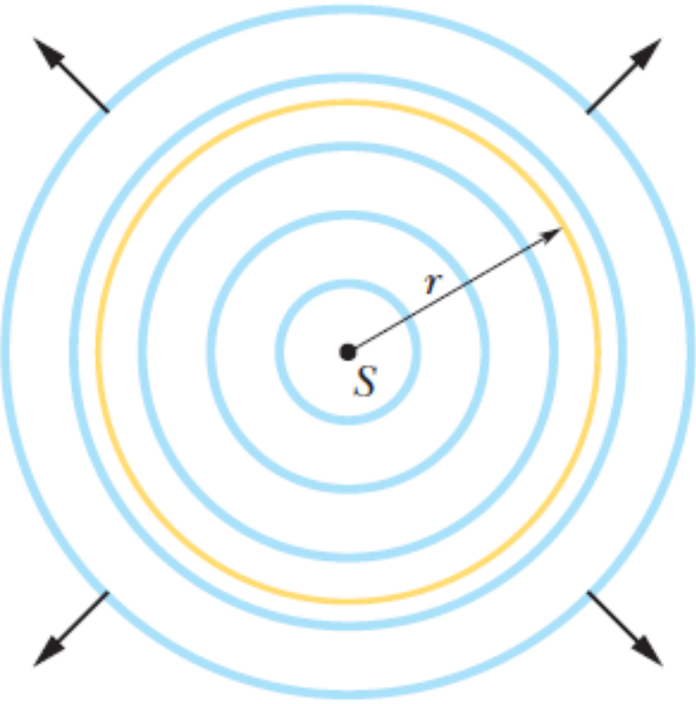
The energy density u (= ½ $\varepsilon_o E^2$) within an electric field, can be written as:

$$u_E = \tfrac{1}{2}\varepsilon_0 E^2 = \tfrac{1}{2}\varepsilon_0 (cB)^2. = \tfrac{1}{2}\varepsilon_0 \frac{1}{\mu_0 \varepsilon_0} B^2 = \frac{B^2}{2\mu_0}$$

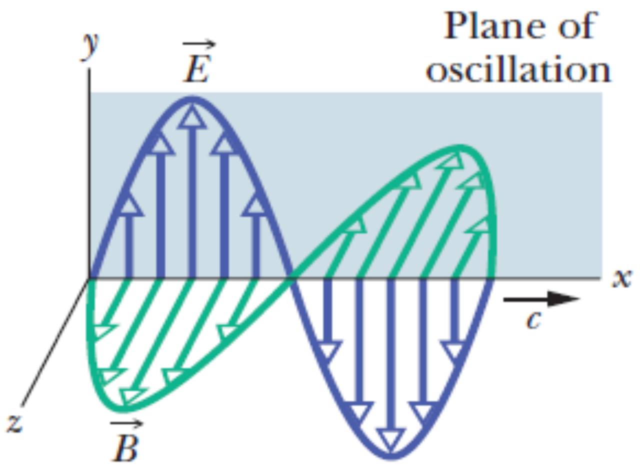
Energy Transport and the Poynting Vector

$$I = \frac{\text{power}}{\text{area}} = \frac{P_s}{4\pi r^2}$$

The energy emitted by light source *S* must pass through the sphere of radius *r*.

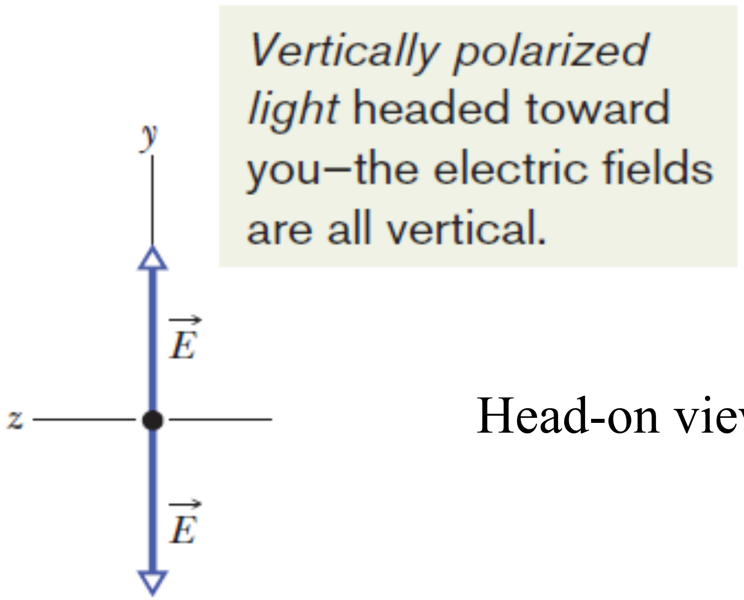


Polarization



(a)

The plane of oscillation of a polarized electromagnetic wave



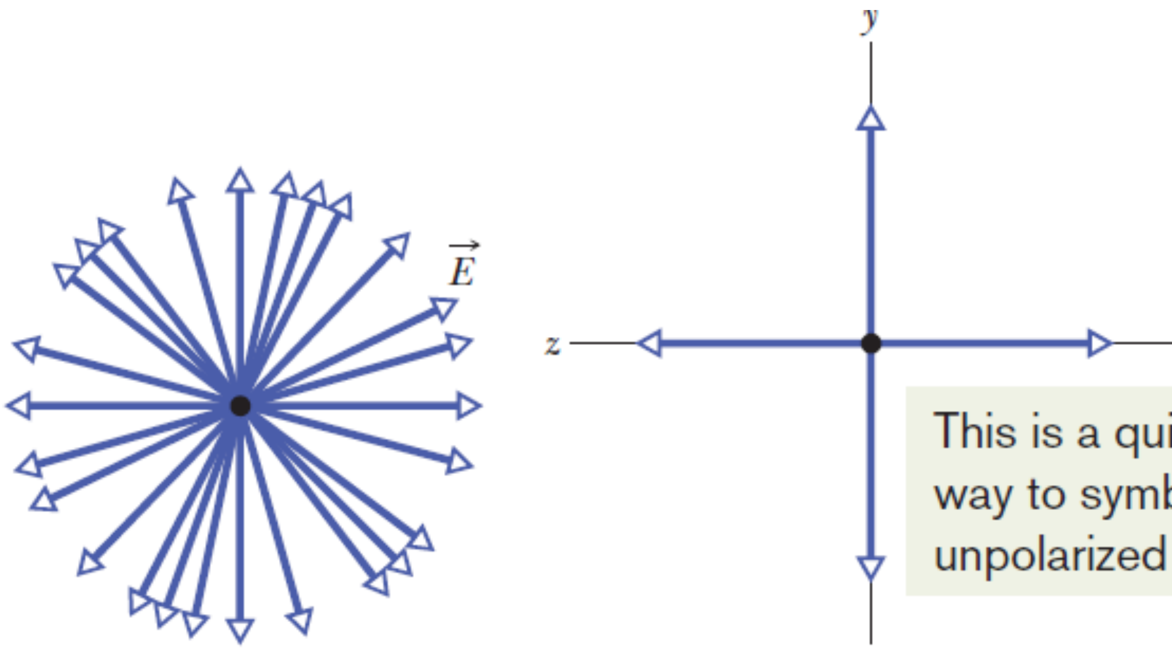
(b)

Head-on view of the plane of polarization

Polarization

An electric field component parallel to the polarizing direction is passed (*transmitted*) by a polarizing sheet; a component perpendicular to it is absorbed.

Unpolarized light headed toward you—the electric fields are in all directions in the plane.



(*a*) (*b*)

This is a quick way to symbolize unpolarized light.

If the intensity of original unpolarized light is I_o, then the intensity of the emerging light through the polarizer, I, is half of that.

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

Polarization: Intensity of Polarized Light

Suppose a polarized light beam reaches a polarizing sheet at an angle θ.

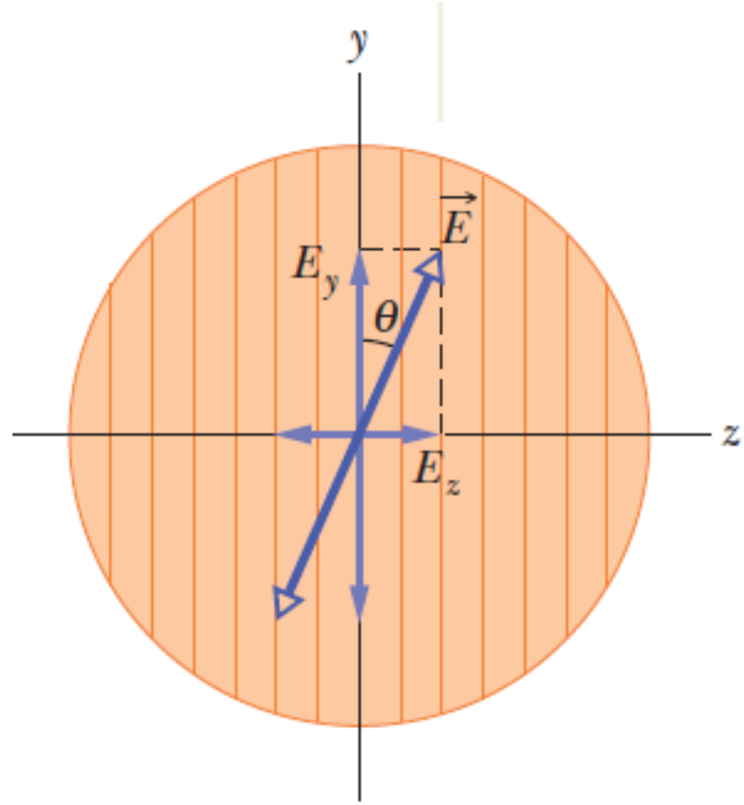
We can resolve ***E*** into two components relative to the polarizing direction of the sheet: parallel component E_y is transmitted by the sheet, and perpendicular component E_z is absorbed. Since θ is the angle between and the polarizing direction of the sheet, the transmitted parallel component is

$$E_y = E\cos\theta.$$

Since

$$I = E_{rms}^2/c\mu_0$$

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



Reflection and Refraction

Reflection:

the reflection angle equals the incident angle

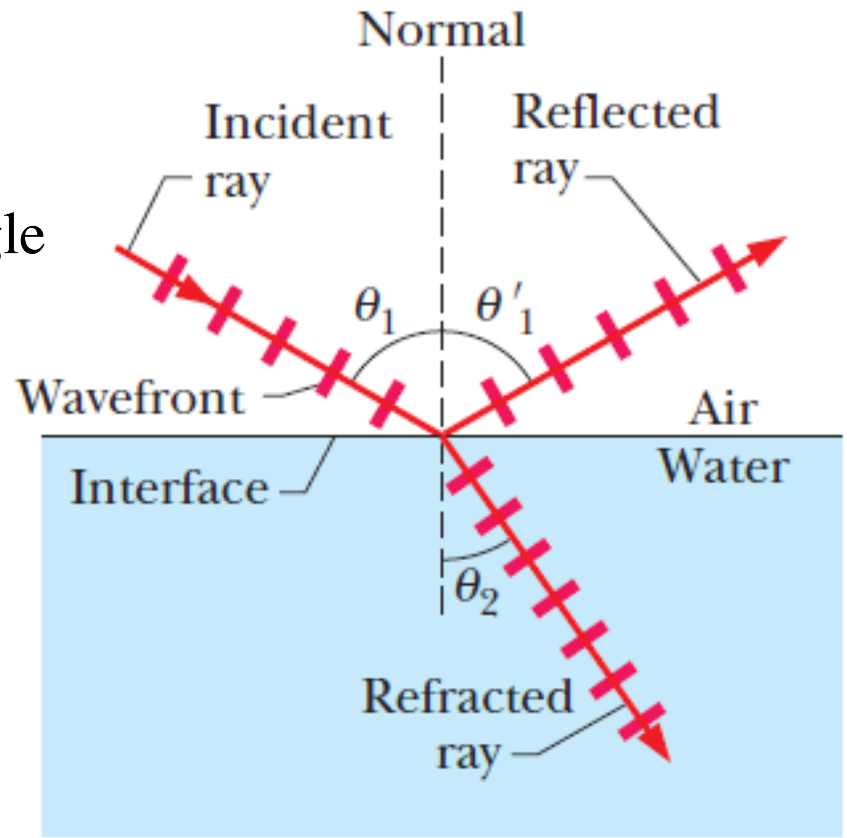
$$\theta_1' = \theta_1$$

Refraction (Snell's law):

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$

n is the index of refraction of the medium:

$$n = \frac{c}{v} \geq 1$$



This is more or less a review of HS physics, but the material is required.

Indexes of Reflection

Table 33-1

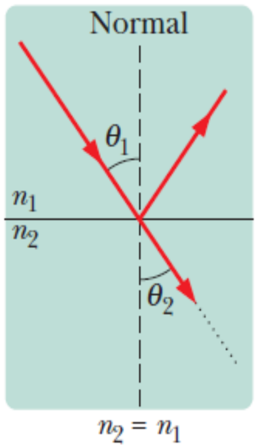
Some Indexes of Refraction[a]

Medium	Index	Medium	Index
Vacuum	Exactly 1	Typical crown glass	1.52
Air (STP)[b]	1.00029	Sodium chloride	1.54
Water (20°C)	1.33	Polystyrene	1.55
Acetone	1.36	Carbon disulfide	1.63
Ethyl alcohol	1.36	Heavy flint glass	1.65
Sugar solution (30%)	1.38	Sapphire	1.77
Fused quartz	1.46	Heaviest flint glass	1.89
Sugar solution (80%)	1.49	Diamond	2.42

[a]For a wavelength of 589 nm (yellow sodium light).

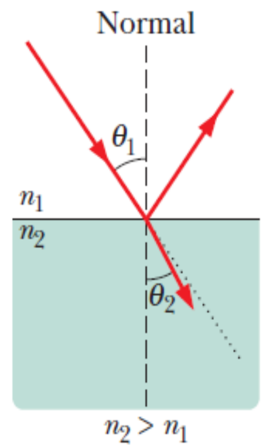
[b]STP means "standard temperature (0°C) and pressure (1 atm)."

Reflection and Refraction



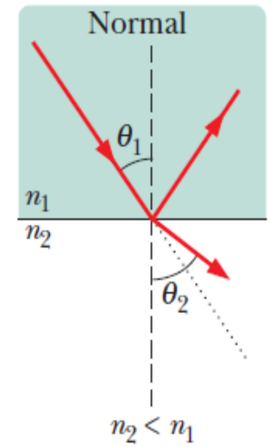
(*a*)

If the indexes match, there is no direction change.



(*b*)

If the next index is greater, the ray is bent *toward* the normal.

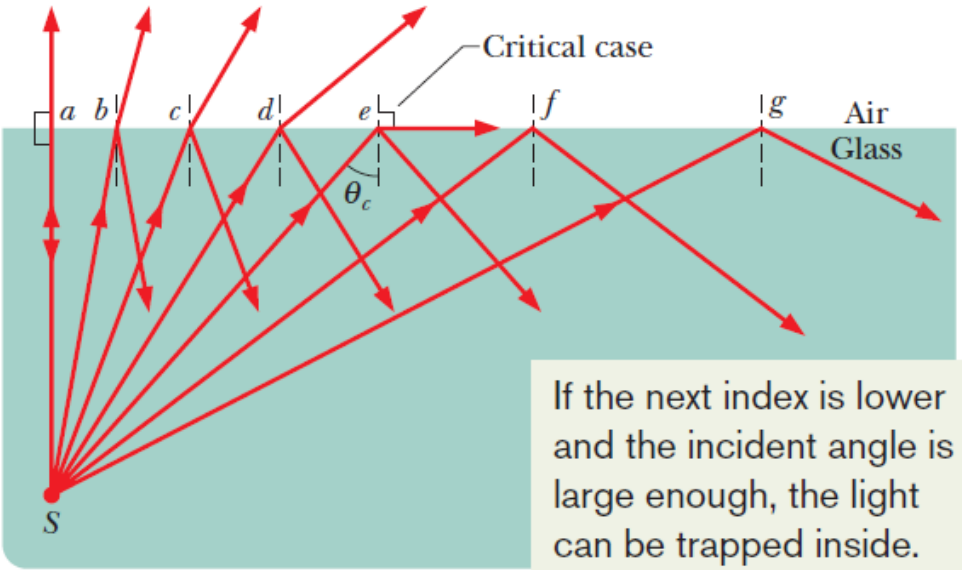


(*c*)

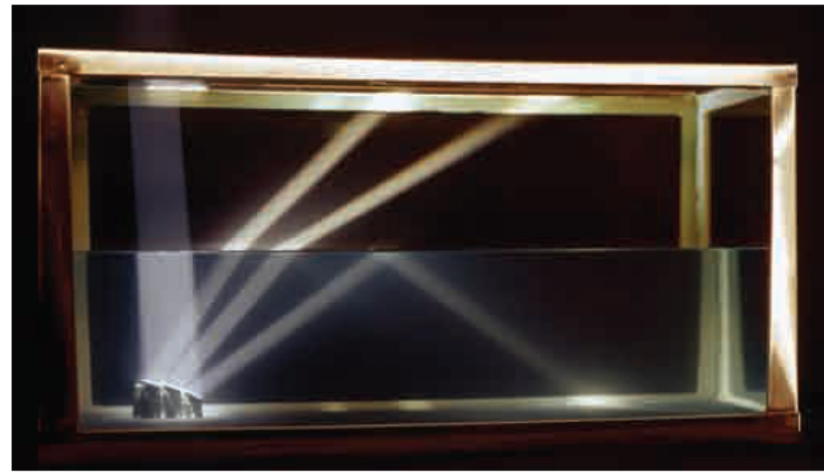
If the next index is less, the ray is bent *away from* the normal.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Total Internal Reflection



(*a*)



(*b*)

For angles of incidence larger than θ_c such as for rays *f* and *g*, there is no refracted ray and all the
light is reflected; this effect is called **total internal reflection.**

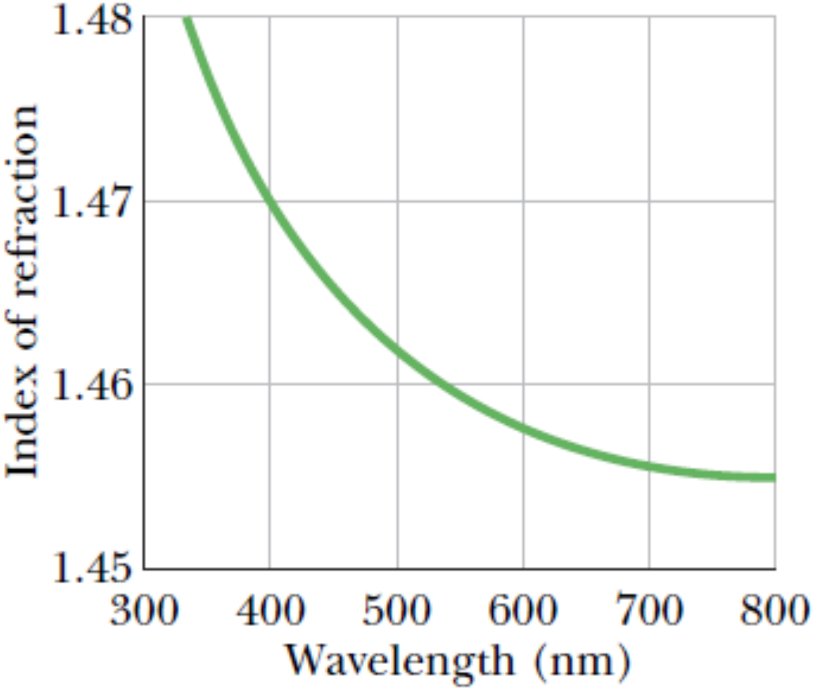
For the critical angle,

$$n_1 \sin \theta_c = n_2 \sin 90°,$$

Which means that

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \qquad \text{(critical angle).}$$

Chromatic Dispersion

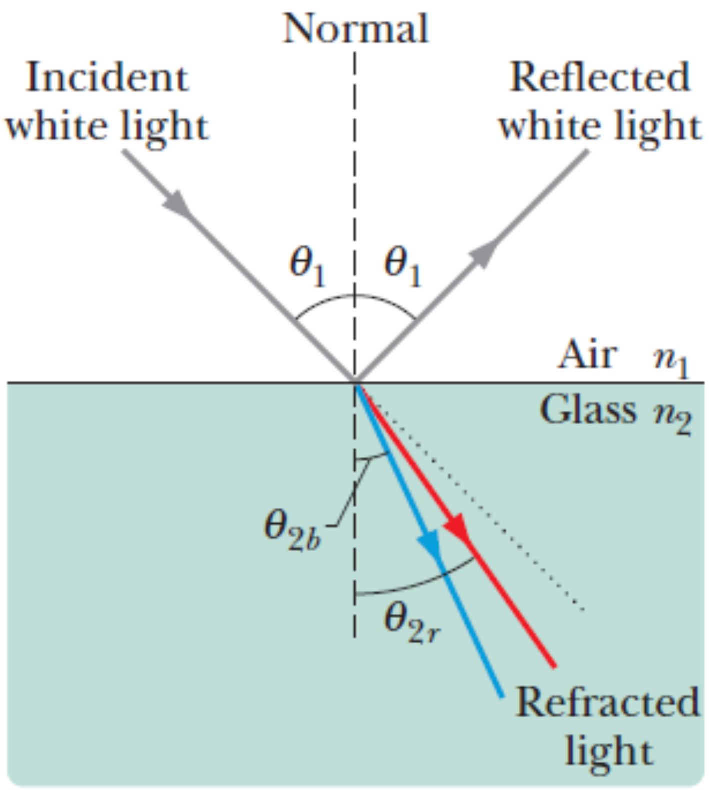


The index of refraction n encountered by light in any medium except vacuum depends on the wavelength of the light.

The dependence of n on light wavelength implies that a light beam of rays of different wavelengths enters the 2^{nd} medium, the rays will be refracted at different angles by a surface; that is, the light will be spread out by the refraction.

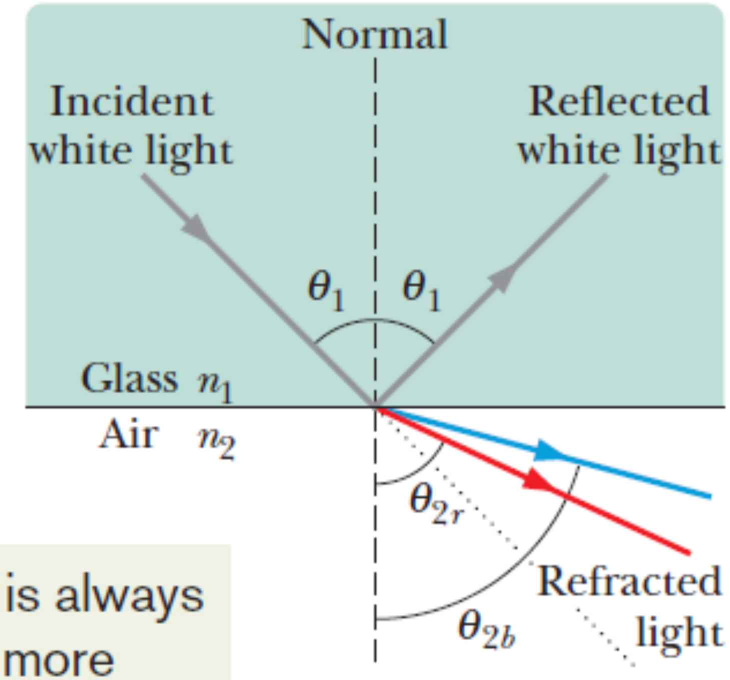
This spreading of light is called **chromatic dispersion**.

Chromatic Dispersion



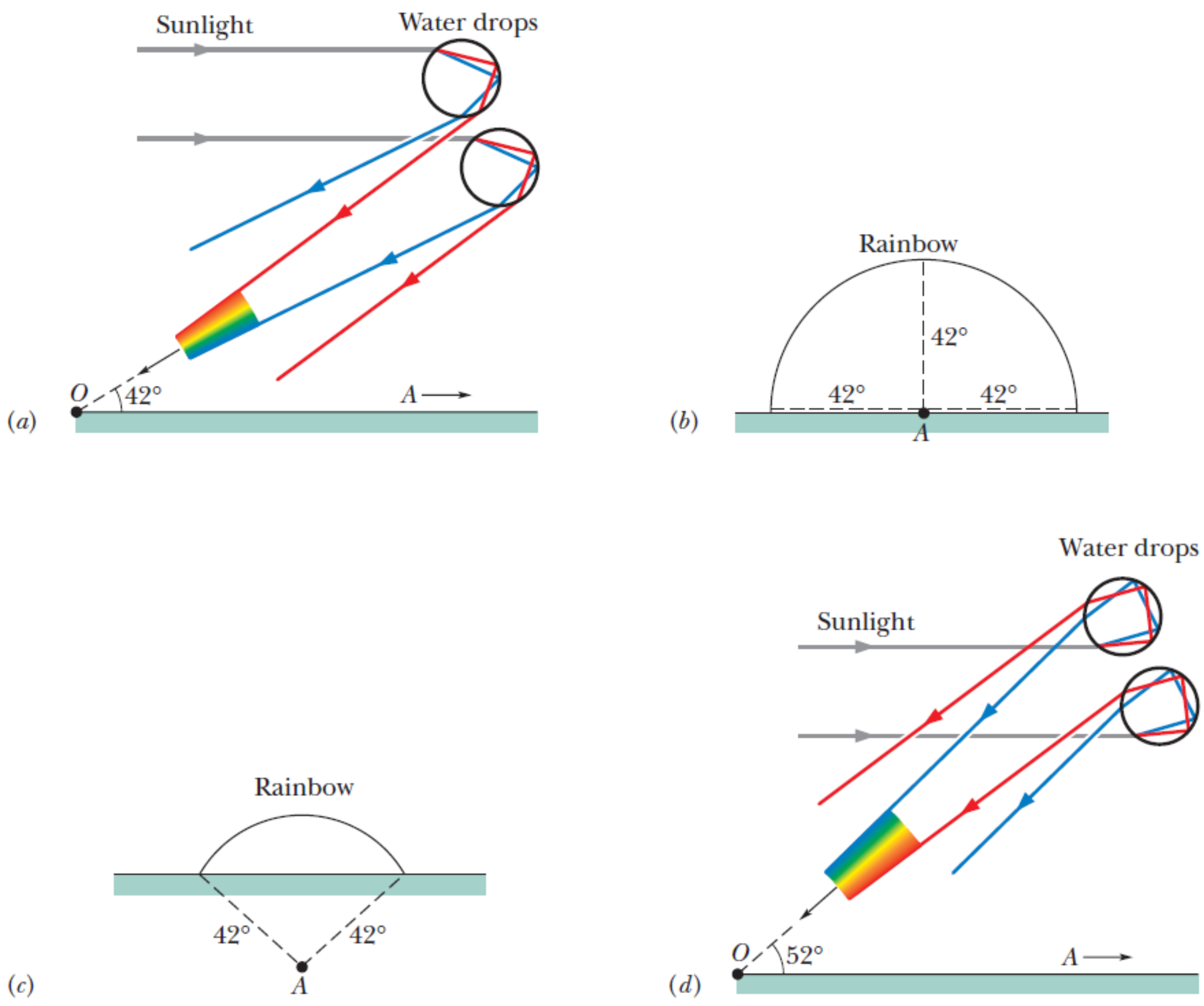
(a)

Blue is always bent more than red.

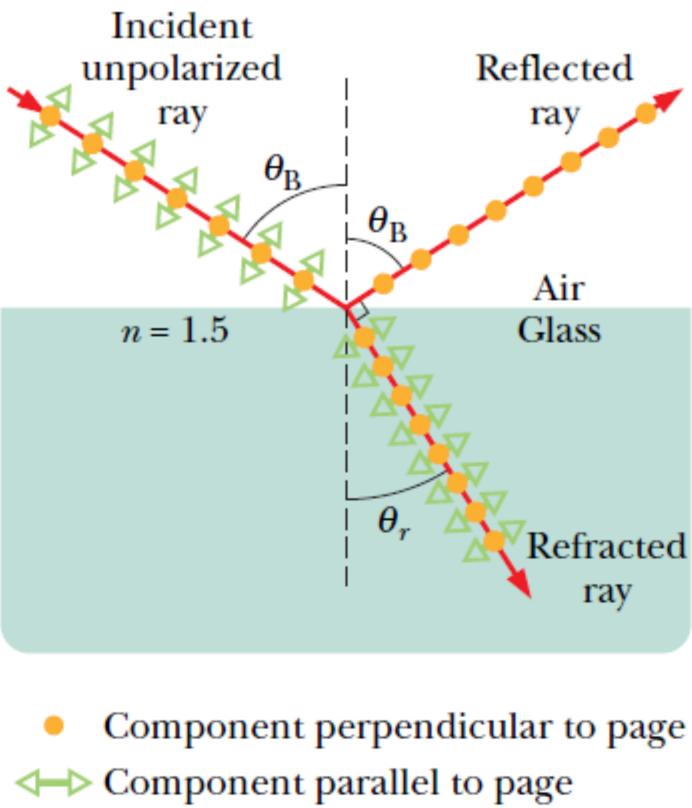


(b)

Chromatic Dispersion in a Rainbow



Polarization by Reflection



A ray of unpolarized light in air is incident on a glass surface at the Brewster angle θ_B. The electric fields along that ray have been resolved into components perpendicular to the page (the plane of incidence, reflection, and refraction) and components parallel to the page. The reflected light consists only of components perpendicular to the page and is thus polarized in that direction. The refracted light consists of the original components parallel to the page and weaker components perpendicular to the page; this light is partially polarized.

$$\theta_B + \theta_r = 90^\circ$$

$$n_1 \sin\theta_B = n_2 \sin\theta_r$$

$$\Rightarrow \quad n_1 \sin\theta_B = n_2 \sin\left(90^\circ - \theta_B\right) = n_2 \cos\theta_B$$

$$\Rightarrow \quad \theta_B = \tan^{-1}\frac{n_2}{n_1} \quad \text{(Brewster angle)}$$