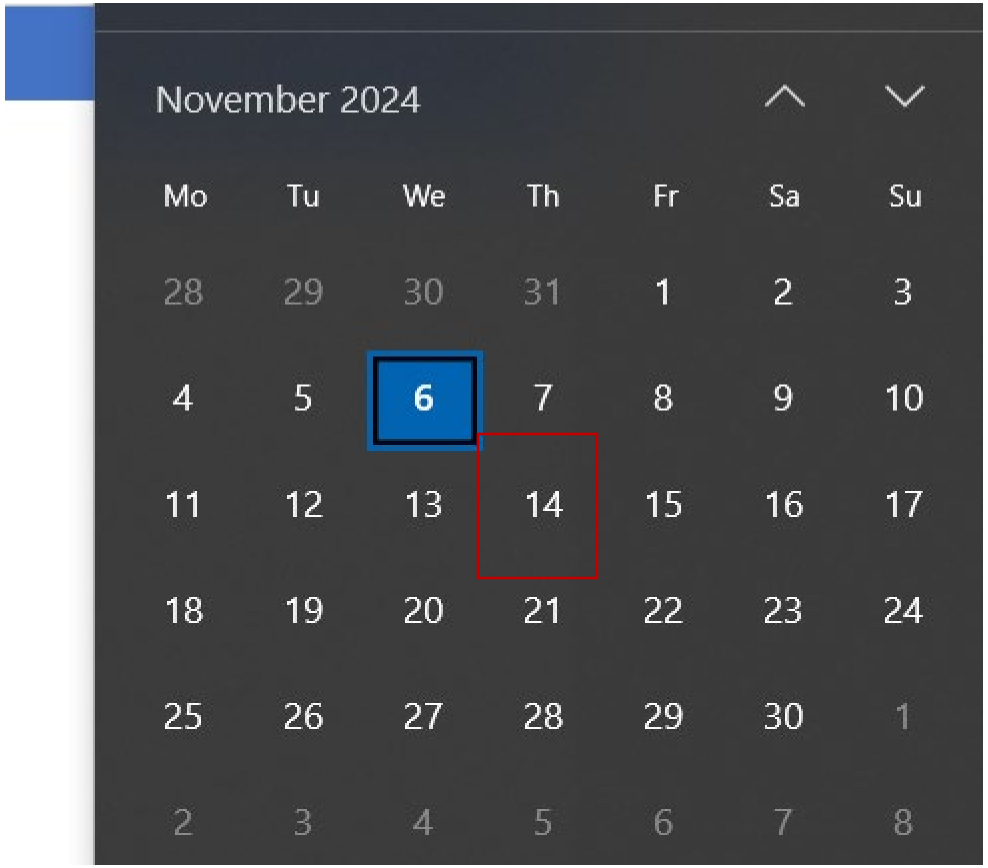
UFUG 1504: Honors General Physics II

Chapter 33

Electromagnetic Waves



Nov. 14 M2 exam,
8:30 pm to 10:30 pm. W4-102

Summary (1 of 7)

Electromagnetic Waves

- An electromagnetic wave consists of oscillating electric and magnetic fields as given by,

$$E = E_m \sin(kx - \omega t)$$ **Equation 33-1**

$$B = B_m \sin(kx - \omega t),$$ **Equation 33-2**

- The speed of any electromagnetic wave in vacuum is c, which can be written as

$$c = \frac{E}{B} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$ **Equation 33-5 & 3**

Summary (2 of 7)

Energy Flow

- The rate per unit area at which energy is trans- ported via an electromagnetic wave is given by the Poynting vector $\vec{S}$:

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}.$$

Equation 33-19

- The intensity I of the wave is:

$$I = \frac{1}{c\mu_0}E_{\text{rms}}^2$$

Equation 33-26

Summary (3 of 7)

- The intensity of the waves at distance r from a point source of power P_s is

$$I = \frac{P_s}{4\pi r^2}.$$

Equation 33-27

Radiation Pressure

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{IA}{c}$$

Equation 33-32

Summary (4 of 7)

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{2IA}{c}$$ **Equation 33-33**

Radiation Pressure

- The radiation pressure p_r is the force per unit area.
- For total absorption

$$p_r = \frac{I}{c}$$ **Equation 33-34**

- For total reflection back along path,

$$p_r = \frac{2I}{c}$$ **Equation 33-35**

Summary (5 of 7)

Polarization

- Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation.
- If the original light is initially unpolarized, the transmitted intensity I is

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

Equation 33-36

- If the original light is initially polarized, the transmitted intensity depends on the angle u between the polarization direction of the original light (the axis along which the fields oscillate) and the polarizing direction of the sheet:

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

Equation 33-26

Summary (6 of 7)

Reflection and Refraction

- The angle of reflection is equal to the angle of incidence, and the angle of refraction is related to the angle of incidence by Snell's law,

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

Equation 33-40

Total Internal Reflection

- A wave encountering a boundary across which the index of refraction decreases will experience total internal reflection if the angle of incidence exceeds a critical angle,

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

Equation 33-45

Summary (7 of 7)

Polarization by Reflection

- A reflected wave will be fully polarized, if the incident, unpolarized wave strikes a boundary at the Brewster angle

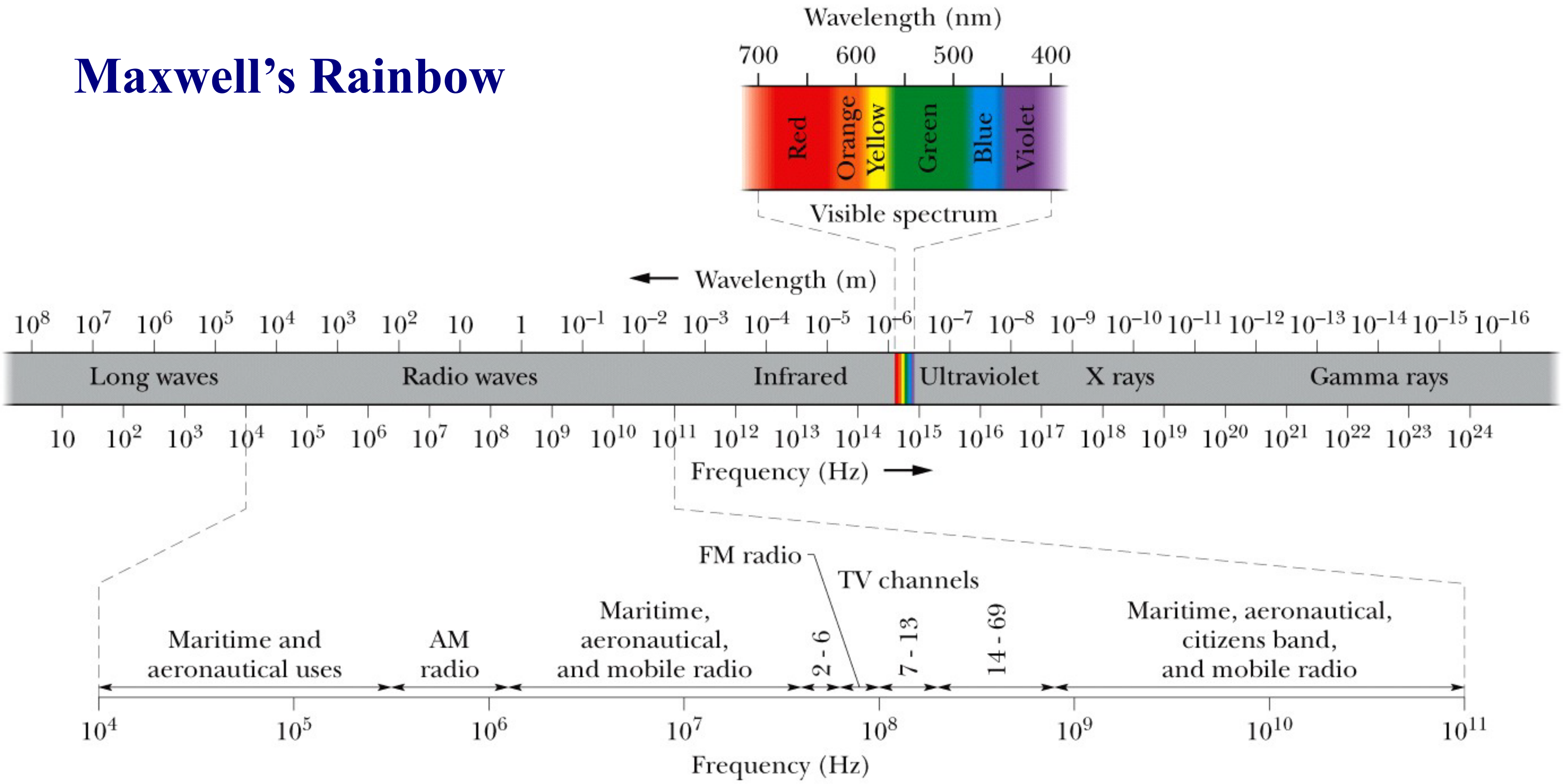
$$\theta_B = \tan^{-1}\frac{n_2}{n_1}$$ **Equation 33-49**

33-1 Electromagnetic Waves (5 of 16)

the visible 可见, infrared (IR) 红外, and ultraviolet (UV) 紫外

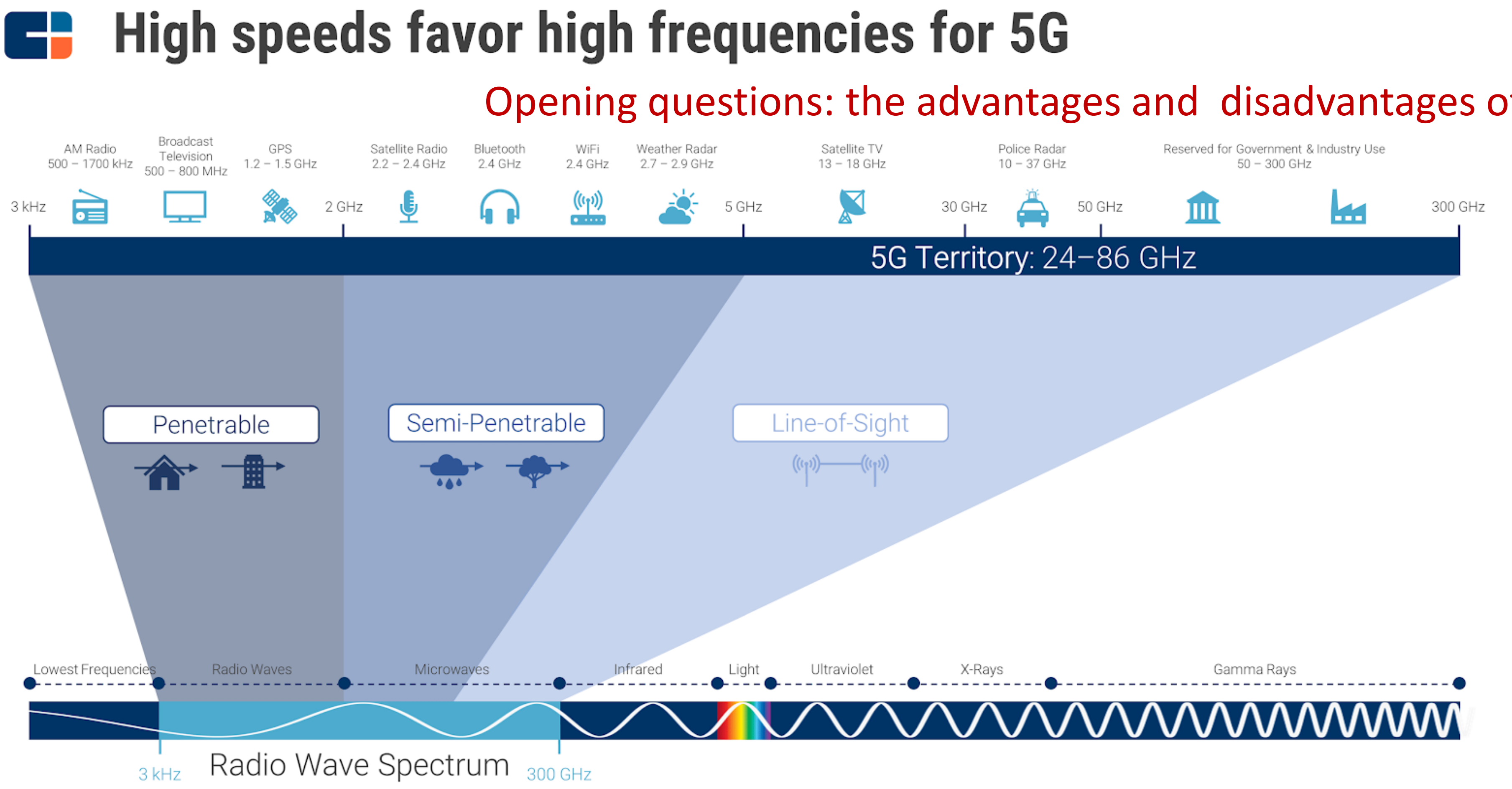
In Maxwell's time (the mid 1800s), the visible 可见, infrared (IR)红外, and ultraviolet (UV)紫外 forms of light were the only electromagnetic waves 电磁波 known. Spurred on by Maxwell's work, however, Heinrich Hertz discovered what we now call radio waves and verified that they move through the laboratory at the same speed as visible light, indicating that they have the same basic nature as visible light. As the figure shows, we now know a wide spectrum (or range) of electromagnetic waves: Maxwell's rainbow.

Maxwell's Rainbow



33-1 Electromagnetic Waves (5 of 16)

Opening questions: the advantages and disadvantages of 5G.



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33-1 Electromagnetic Waves (5 of 16)

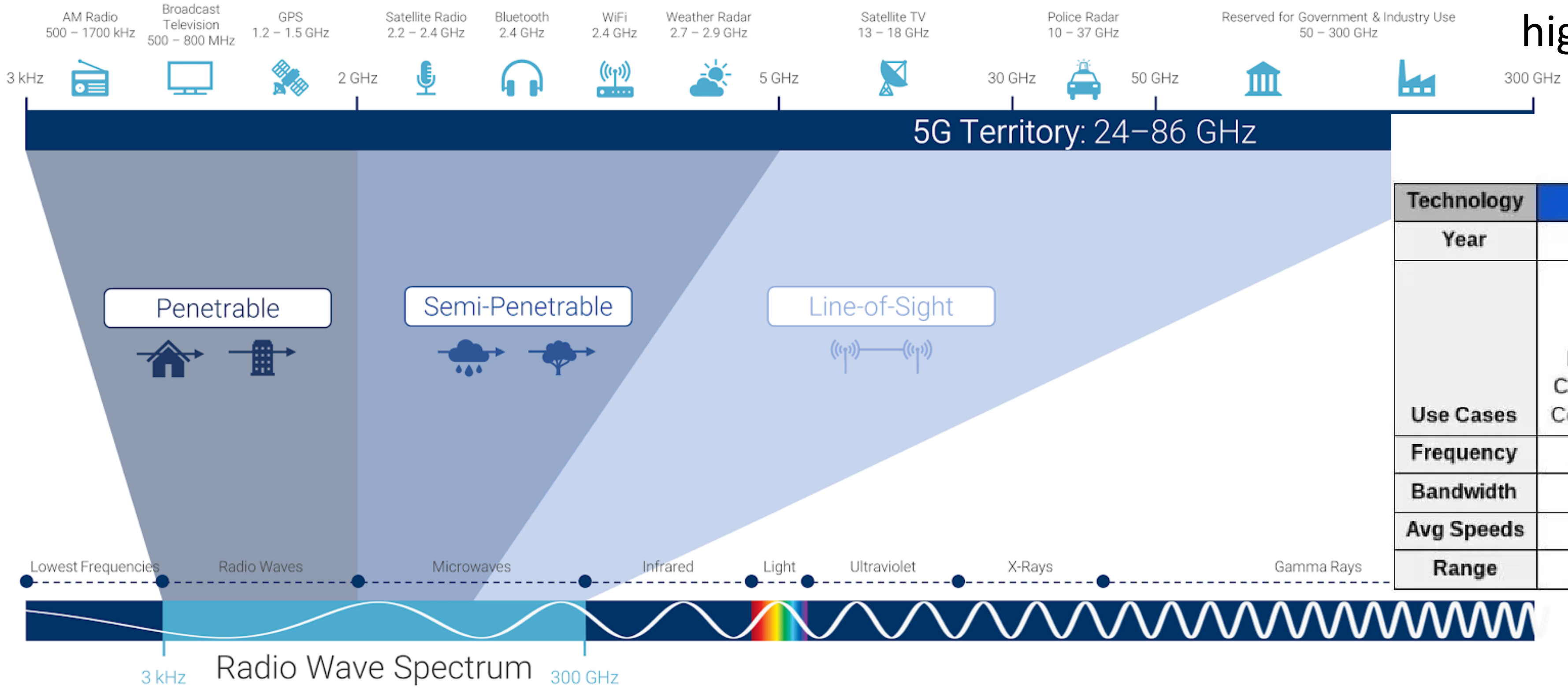
Adv. : higher speeds and lower latency

Disadv. : limited coverage, e.g. 4G 1~3 km/per

5G hundreds of meters/per

high infrastructure costs

High speeds favor high frequencies for 5G



1 Gb = 1,000 Mb = 1,000,000 kb = 1,000,000,000 Bits

UPDATE

Technology	1G	2G	3G	4G	5G
Year	1979	1991	2001	2009	2019
Use Cases	Analog System, Dropped Calls, Giant Cell Phones	Texting (SMS), MMS, Conference Calls, Long Distance Call Tracking	Cheap data transmission, GPS, Web Browsing, SD Video Streaming	HD Video Streaming, Wearable Devices, High Speed Applications	Internet of Things, Clou Storage, Remote Surgical Robots
Frequency	30 KHz	1.8 GHz	1.6-2 GHz	2-8 GHz	3-30 GHz
Bandwidth	2 kbps	364 kbps	3 Mbps	100 Mbps	10 Gbps
Avg Speeds	2 kbps	40 kbps	300 kbps	25 Mbps	150 Mbps
Range	N/A	50 mi	35 miles	10 miles	1,000 ft

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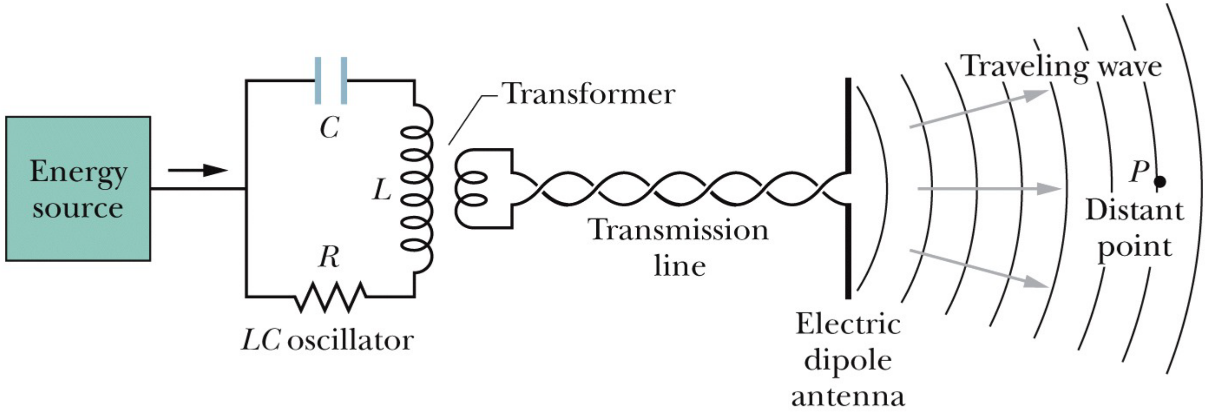
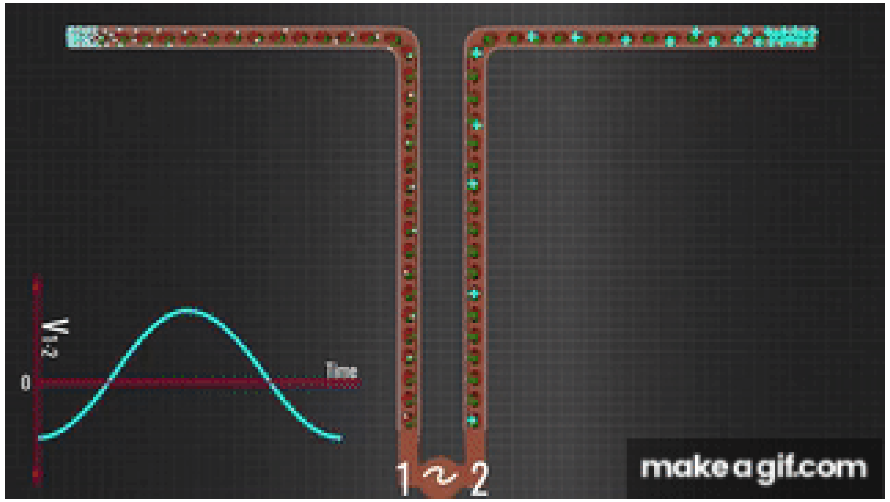
33-1 Electromagnetic Waves (6 of 16)

Travelling Electromagnetic Wave



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 (天线), which generates the wave. *P* is a distant point at which a detector can monitor the wave traveling past it.



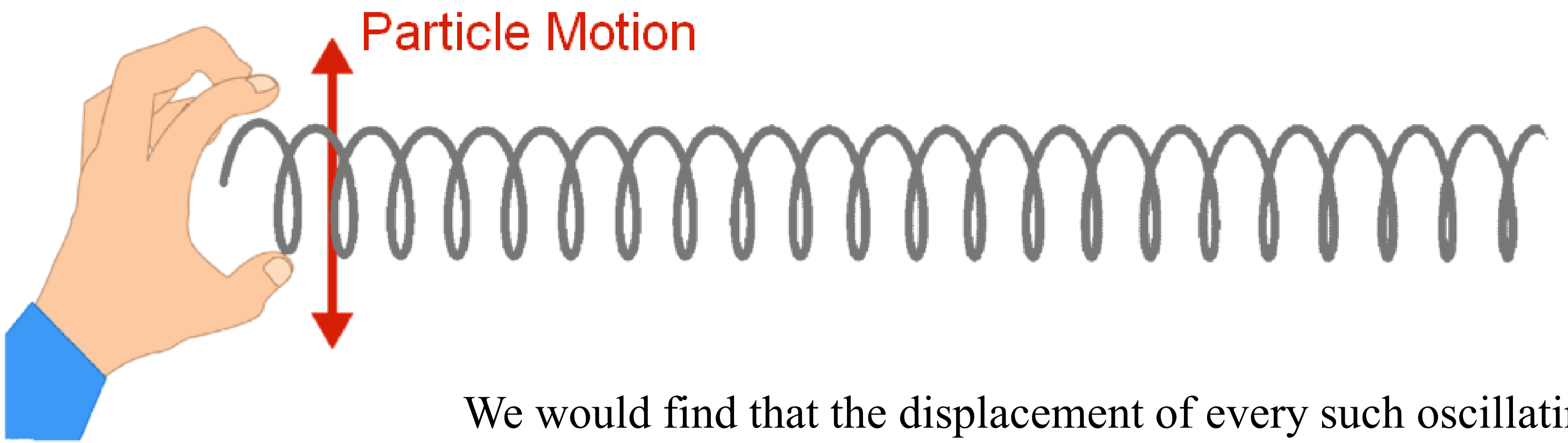
How does an Antenna work?

1. *LC oscillator*, produces sinusoidally charges and currents with angular frequency ω (= 1/√LC).

2. *LC oscillator* coupling with antenna, thus charge/current in antenna also oscillate sinusoidally

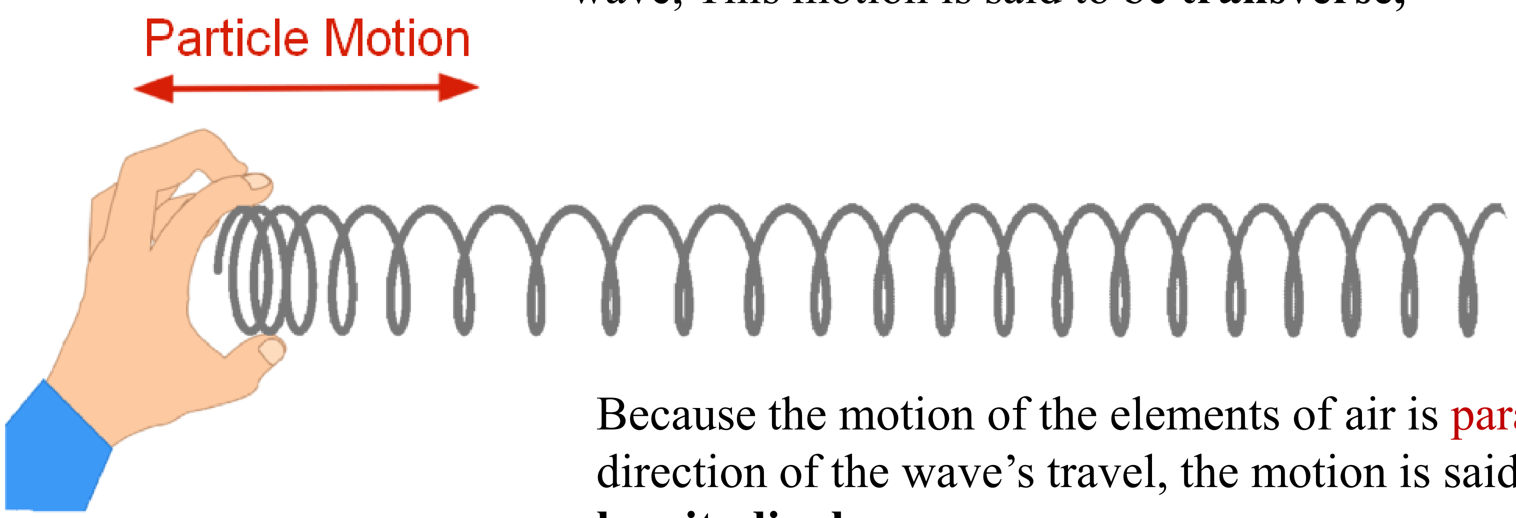
3. Produces travelling electromagnetic wave with speed c and angular frequency ω.

16-1 Transverse Waves (7 of 11)



(a) Transverse Wave 横波

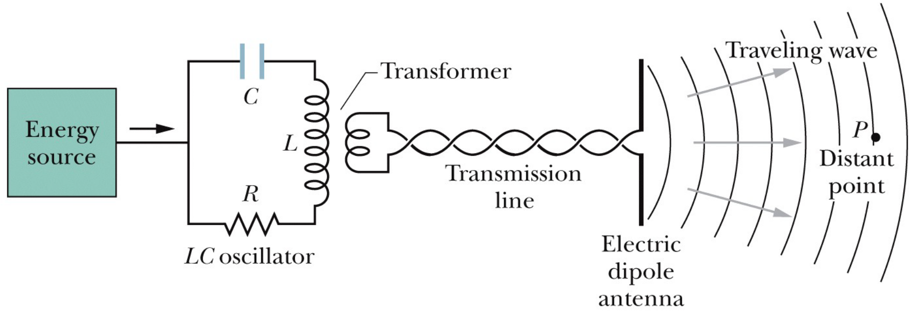
We would find that the displacement of every such oscillating string element is *perpendicular* to the direction of travel of the wave, This motion is said to be **transverse,**

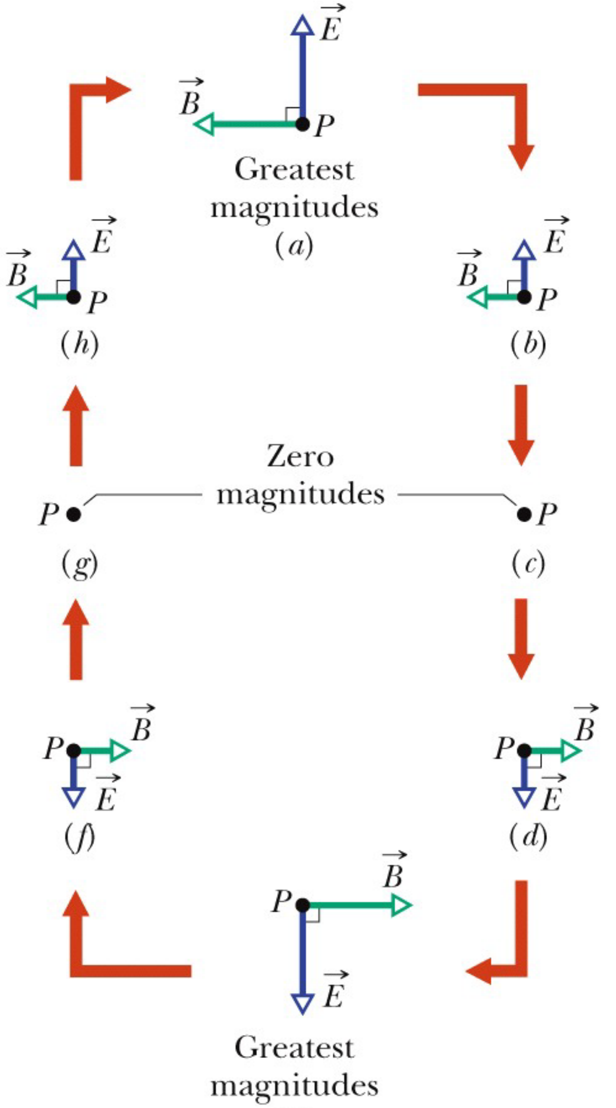


(b) Longitudinal Wave 纵波

Because the motion of the elements of air is parallel to the direction of the wave's travel, the motion is said to be **longitudinal,**

33-1 Electromagnetic Waves (8 of 16)



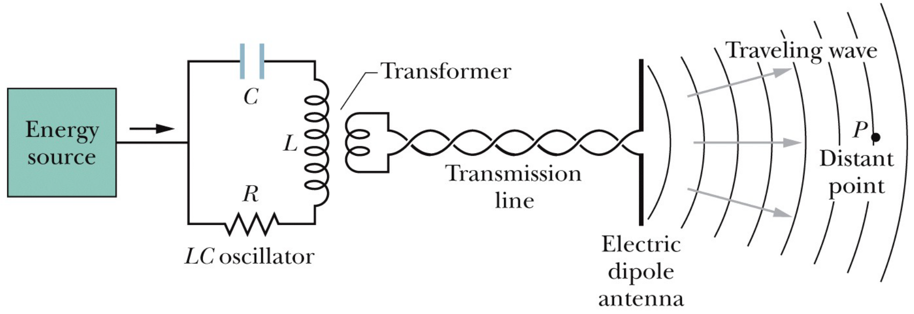


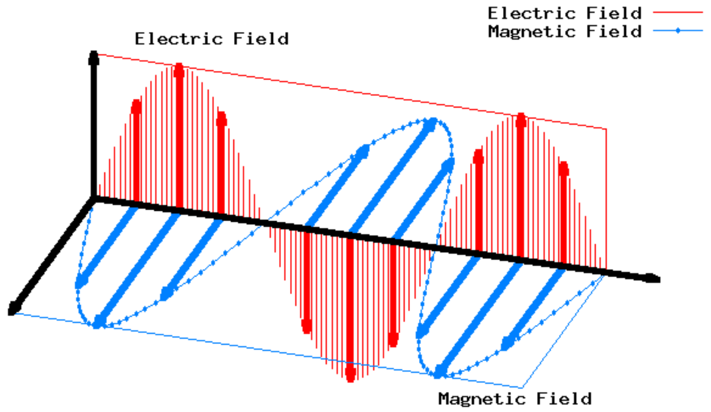
Electromagnetic Wave. Figure 1 shows how the electric field $\vec{E}$ and the magnetic field $\vec{B}$ change with time as one wavelength of the wave sweeps past the distant point P of Figure 2 ; in each part of Figure 1, the wave is traveling directly out of the page.

Note several key features of the wave :

1. The electric and magnetic fields $\vec{E}$ and $\vec{B}$ are always perpendicular to the direction in which the wave is traveling. Thus, the wave is a transverse wave (橫波).
2. The electric field is always perpendicular to the magnetic field.
3. The cross product $\vec{E} \times \vec{B}$ always gives the direction in which the wave travels.
4. The fields always vary sinusoidally, just like the transverse waves. Moreover, the fields vary with the same frequency.

33-1 Electromagnetic Waves (8 of 16)





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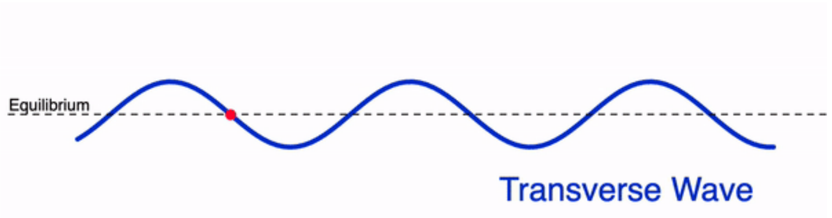
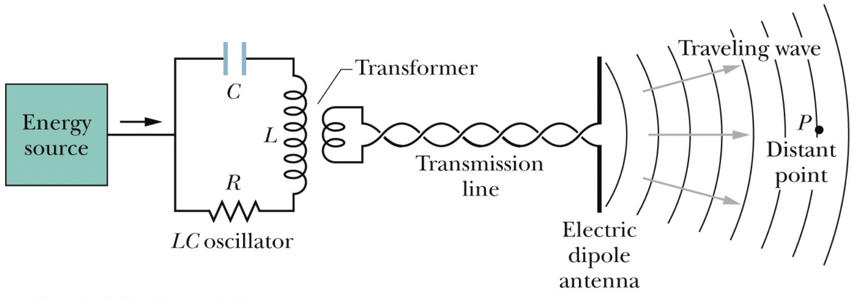
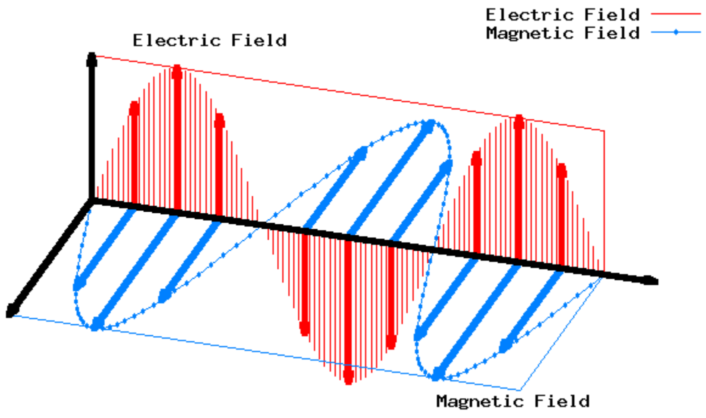


1. The electric and magnetic fields $\vec{E}$ and $\vec{B}$ are always perpendicular to the direction in which the wave is traveling. Thus, the wave is a transverse wave (横波).
2. The electric field is always perpendicular to the magnetic field.
3. The cross product $\vec{E} \times \vec{B}$ always gives the direction in which the wave travels. （Poynting Vector 33-2）
4. The fields always vary sinusoidally, just like the transverse waves. Moreover, the fields vary with the same frequency.

33-1 Electromagnetic Waves (13 of 16)





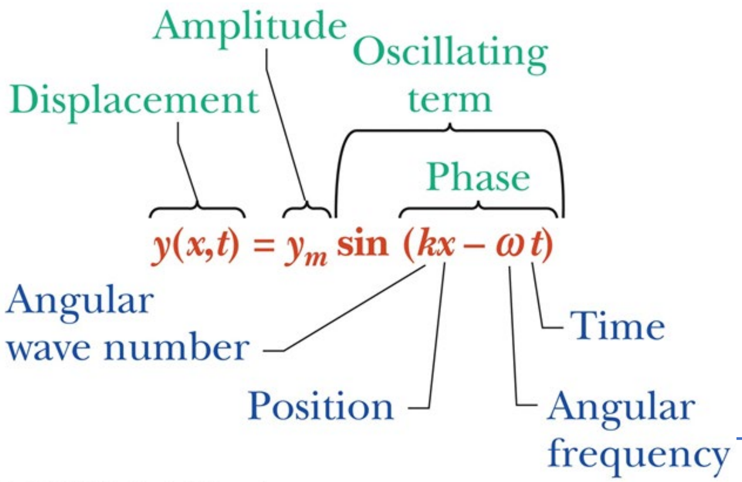
In keeping with these features, we can deduce that an electromagnetic wave traveling along an x axis has an electric field $\vec{E}$ and a magnetic field $\vec{B}$ with magnitudes that depend on x and t:

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

$$B = B_m \sin(kx - \omega t), \qquad \omega\ (= 1/\sqrt{LC}\ ).$$

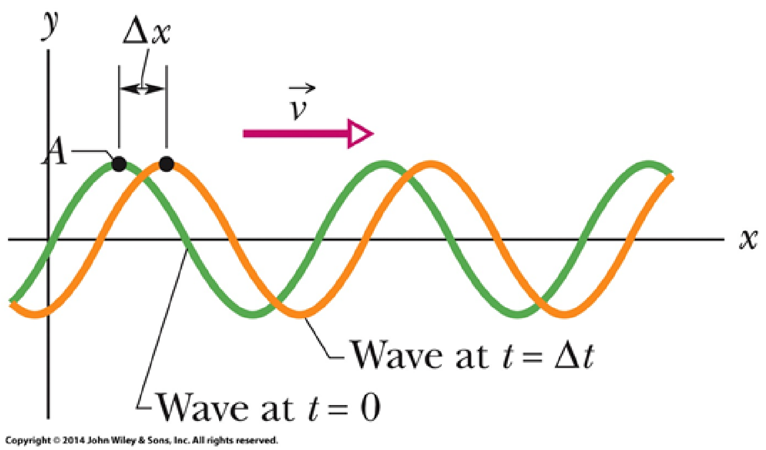
where E_m and B_m are the amplitudes of $\vec{E}$ and $\vec{B}$.

The electric field induces the magnetic field and vice versa (反之亦然).



16-1 Transverse Waves (10 of 11)

- **The Speed of a Traveling Wave**



$$y(x, t) = y_m \sin(kx - \omega t).$$

- Two snapshots of the wave: at time $t = 0$, and then at time $t = \Delta t$.
- As the wave moves to the right at velocity v, the entire curve shifts a distance Δx during Δt.

$kx - \omega t = constant$ ⇒ $k(dx/dt) - \omega = constant$

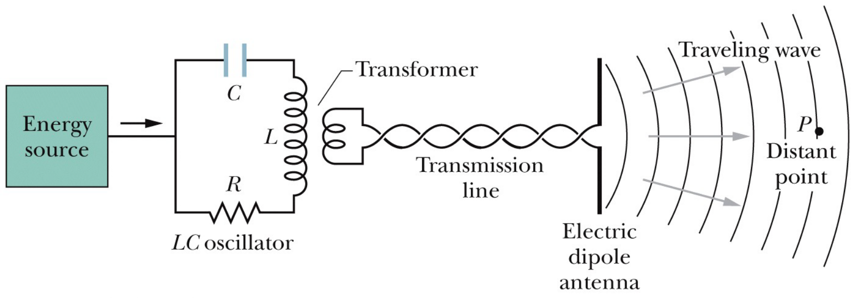
$$\boxed{v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f \qquad (\text{wave speed}).}$$

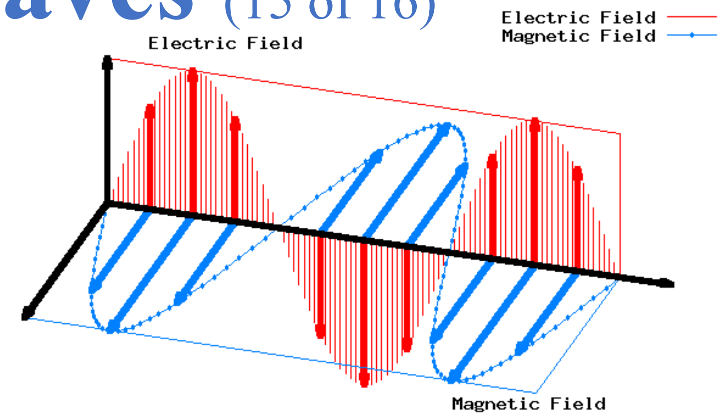
$$\omega = \frac{2\pi}{T} \quad .$$

$$k = \frac{2\pi}{\lambda} \quad .$$

$$y(x, t) = y_m \sin(kx + \omega t).$$ a wave traveling in the negative direction of x

33-1 Electromagnetic Waves (15 of 16)





Wave Speed. From chapter 16, we know that the speed of the wave is $\frac{\omega}{k}$.
However, because this is an electromagnetic wave, its speed (in vacuum) is given the symbol *c* rather than *v* and that *c* has the value given by

we find that the magnitudes of the fields at every instant and at any point are related by

$$\frac{E}{B} = c \quad \text{(magnitude ratio).}$$

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

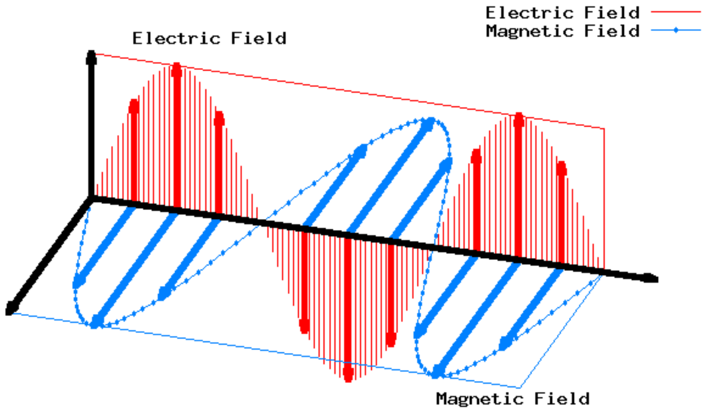
which is about 3.0×10^8 m/s.

In other words, All electromagnetic waves, including visible light, have the same speed *c* in vacuum.

33-1 Electromagnetic Waves (15 of 16)

How to prove this two question?

$$\frac{E}{B} = c \quad \text{(magnitude ratio)}. \qquad c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad \text{(wave speed)},$$



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

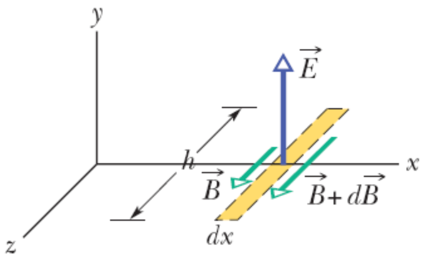


Figure 33-7 The sinusoidal variation of the electric field through this rectangle, located (but not shown) at point P in Fig. 33-5b, induces magnetic fields along the rectangle. The instant shown is that of Fig. 33-6: $\vec{E}$ is decreasing in magnitude, and the magnitude of the induced magnetic field is greater on the right side of the rectangle than on the left.

apply Faraday's law of induction,

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

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

$$\Phi_B = (B)(h\,dx),$$

$$\frac{d\Phi_B}{dt} = h\,dx\,\frac{dB}{dt}$$

$$h\,dE = -h\,dx\,\frac{dB}{dt} \quad \text{Thus} \quad \frac{dE}{dx} = -\frac{dB}{dt}$$

33-1 Electromagnetic Waves (15 of 16)

$$\frac{dE}{dx} = -\frac{dB}{dt}$$

because $E = E_m \sin(kx - \omega t)$, $\quad B = B_m \sin(kx - \omega t)$,

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

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

Thus $\quad \dfrac{E}{B} = c \quad$ (magnitude ratio).

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

apply Maxwell's law of induction,

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

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

$$\Phi_E = (E)(h\,dx),$$

$$\frac{d\Phi_E}{dt} = h\,dx\,\frac{dE}{dt}.$$

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

33-1 Electromagnetic Waves (15 of 16)

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

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

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

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

because $\frac{E}{B} = c$ (magnitude ratio).

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

33-2 Energy Transport and The Poynting Vector 玻印亭矢量

The Poynting Vector: The rate per unit area at which energy is transported via an electromagnetic wave is given by the Poynting vector

The rate of energy transport per unit area in a wave

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$$

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.

33-2 Energy Transport and The Poynting Vector (5 of 9)

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$$

Because E and B are perpendicular to each other in an electromagnetic wave.

Then the magnitude of S is

$$S = \frac{1}{\mu_0} EB$$

$$\frac{E}{B} = c \quad \text{(magnitude ratio).}$$

$$S = \frac{1}{c\mu_0} E^2$$

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

an equation for the energy transport rate as a function of time

33-2 Energy Transport and The Poynting Vector (5 of 9)

More useful in practice, however, is the average energy transported over time

The time-averaged rate per unit area at which energy is transported is S_{avg}, which is called the intensity I of the wave:

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

in which $E_{\text{rms}} = \dfrac{E_m}{\sqrt{2}}.$

E_{rms} is the root-mean-square value of the electric field

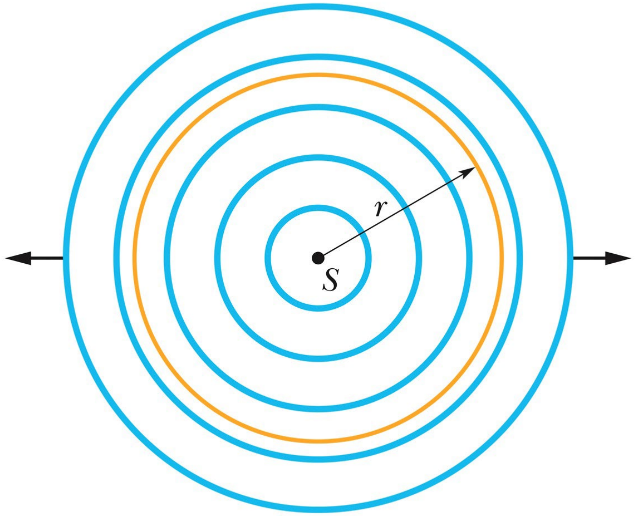
derivative process $I = S_{\text{avg}} = \dfrac{1}{c\mu_0}[E^2]_{\text{avg}} = \dfrac{1}{c\mu_0}[E_m^2 \sin^2(kx - \omega t)]_{\text{avg}}.$

17-4 Intensity and Sound Level (4 of 6)

- The intensity at a distance *r* from a point source that emits sound waves of power P_s equally in all directions isotropically i.e. with equal intensity in all directions,

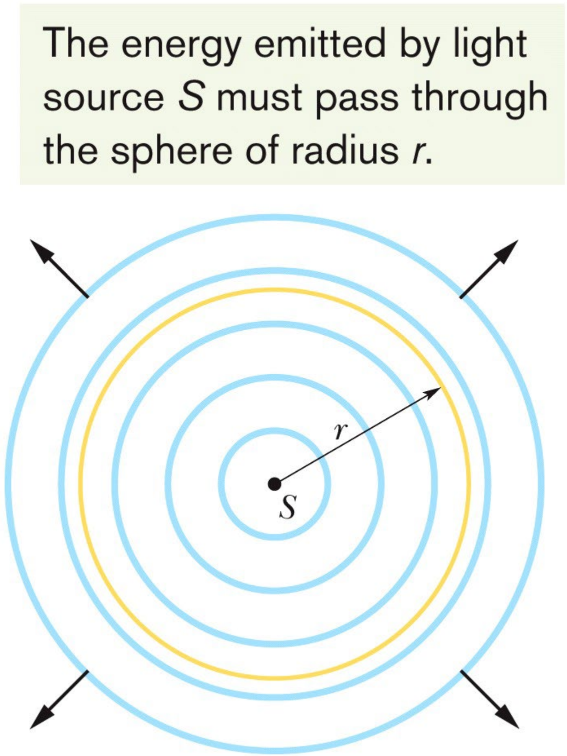
$$I = \frac{P}{A}, \quad \Rightarrow \quad I = \frac{P_s}{4\pi r^2},$$

where $4\pi r^2$ is the area of the sphere.



A point source *S* emits sound waves uniformly in all directions. The waves pass through an imaginary sphere of radius *r* that is centered on *S*.

33-2 Energy Transport and The Poynting Vector (6 of 9)



A point source of electromagnetic waves emits the waves isotropically—that is, with equal intensity in all directions. The intensity of the waves at distance r from a point source of power P_s is

The intensity of the waves $$I = \frac{\text{power}}{\text{area}} = \frac{P_s}{4\pi r^2},$$

When you look at the North Star (Polaris), you intercept light from a star at a distance of 431 ly and emitting energy at a rate of 2.2×10^3 times that of our Sun ($P_{Sun} = 3.90 \times 10^{26}$ W). Neglecting any atmospheric absorption, find the rms values of the electric and magnetic fields when the starlight reaches you.

When you look at the North Star (Polaris), you intercept light from a star at a distance of 431 ly and emitting energy at a rate of 2.2 × 10₃ times that of our Sun (P_{Sun} = 3.90 ×10^{26} W). Neglecting any atmospheric absorption, find the rms values of the electric and magnetic fields when the starlight reaches you.

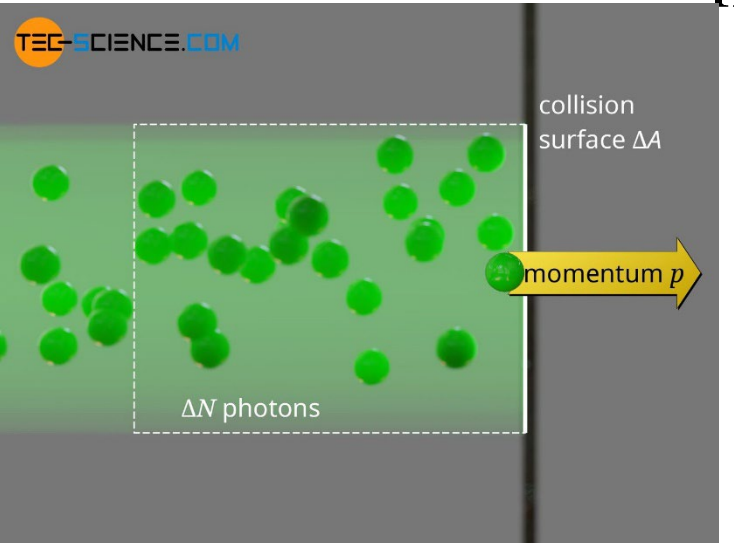
$$I = \frac{P_s}{4\pi r^2}, \qquad I = \frac{1}{c\mu_0} E_{\text{rms}}^2.$$

$$E_{\text{rms}} = \sqrt{\frac{P_s c \mu_0}{4\pi r^2}}$$

$$E_{\text{rms}} = 1.24 \times 10^{-3}\ \text{V/m} \approx 1.2\ \text{mV/m}.$$

$$\frac{E}{B} = c \quad \text{(magnitude ratio).} \qquad B_{\text{rms}} = \frac{E_{\text{rms}}}{c} = \frac{1.24 \times 10^{-3}\ \text{V/m}}{3.00 \times 10^{8}\ \text{m/s}} = 4.1 \times 10^{-12}\ \text{T} = 4.1\ \text{pT}.$$

33-2 Energy Transport and The Poynting Vector (8 of 9)



When a surface intercepts(拦截) electromagnetic radiation, a force and a pressure are exerted on the surface.

If the radiation is totally absorbed by the surface, the force is

$$F = \frac{IA}{c} \qquad \text{Total Absorption}$$

in which I is the intensity of the radiation and A is the area of the surface perpendicular to the path of the radiation.

If the radiation is totally reflected back along its original path, the force is

$$F = \frac{2IA}{c} \qquad \text{Total Reflection back along path}$$

33-2 Energy Transport and The Poynting Vector (8 of 9)

$$F = \frac{IA}{c} \qquad \text{Total Absorption}$$

A change in momentum is related to a force

$$F = \frac{\Delta p}{\Delta t}$$

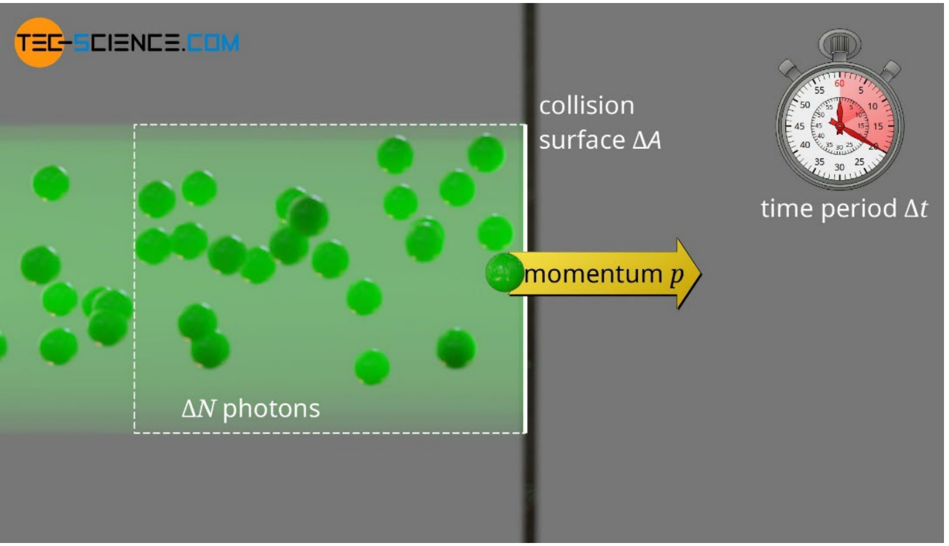
In time interval Δt, the energy intercepted by area A is

$$\Delta U = IA\ \Delta t.$$

$$\Delta p = \frac{\Delta U}{c} \qquad \text{(total absorption)}$$

$$\Delta p = IA\ \Delta t/c.$$

$$F = \frac{IA}{c} \qquad \text{(total absorption).}$$



14-1 Fluid Density and Pressure (4 of 6)

- The **pressure**, force acting on an area, is defined as:

$$P = \frac{\Delta F}{\Delta A}.$$

- **Equation (14-3)**

- We could take the limit of this for infinitesimal area, but if the force is uniform over a flat area *A* we write

$$P = \frac{F}{A}$$

- **Equation (14-4)**

  - We can measure pressure with a sensor

33-2 Energy Transport and The Poynting Vector (9 of 9)

The **radiation pressure** p_r is the force per unit area:

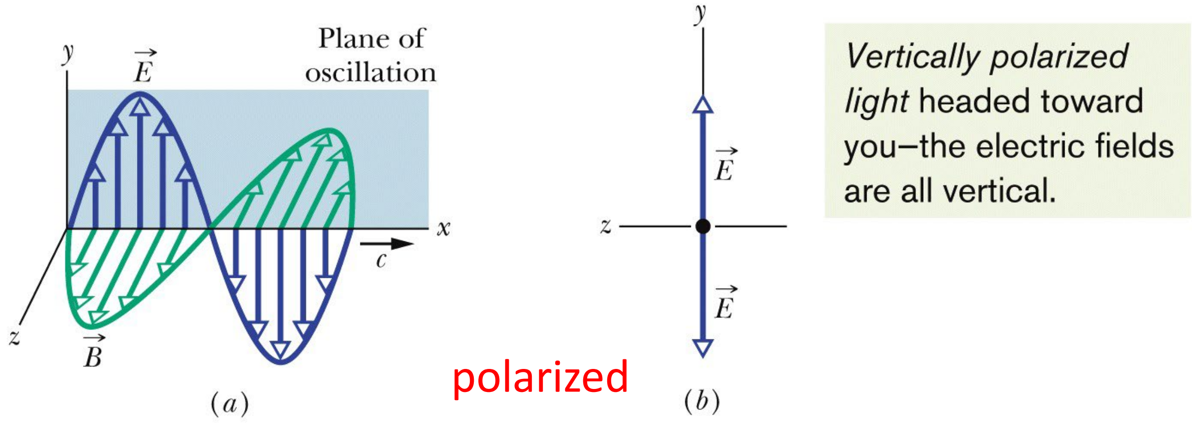
$$P = \frac{\Delta F}{\Delta A}.$$

$$F = \frac{IA}{c} \quad \Rightarrow \quad p_r = \frac{I}{c}$$ Total Absorption

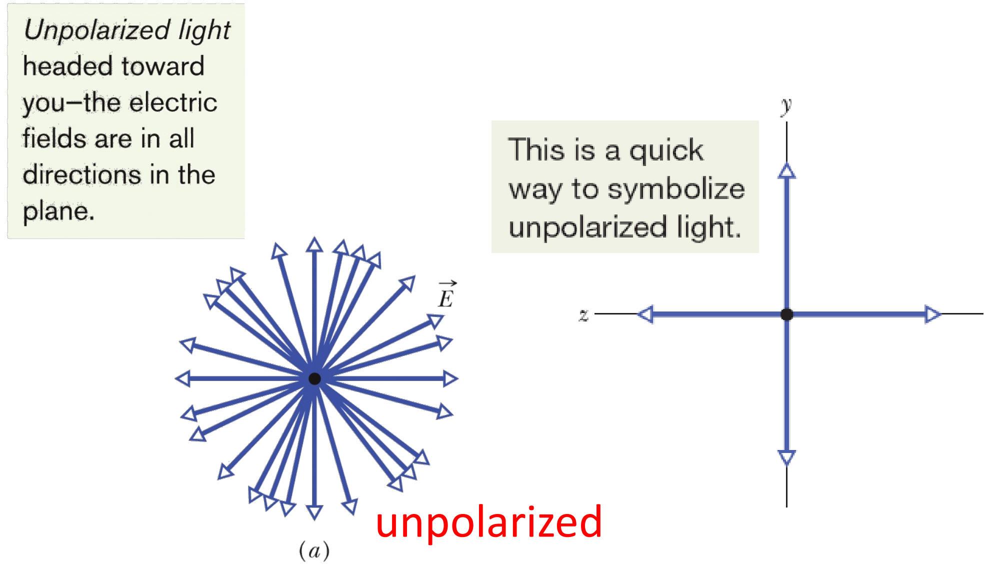
$$F = \frac{2IA}{c} \quad \Rightarrow \quad p_r = \frac{2I}{c}$$ Total Reflection back along path

33-4 Polarization (极化)(3 of 4)

Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation. Light waves from common sources are not polarized; that is, they are unpolarized, or polarized randomly.



polarized

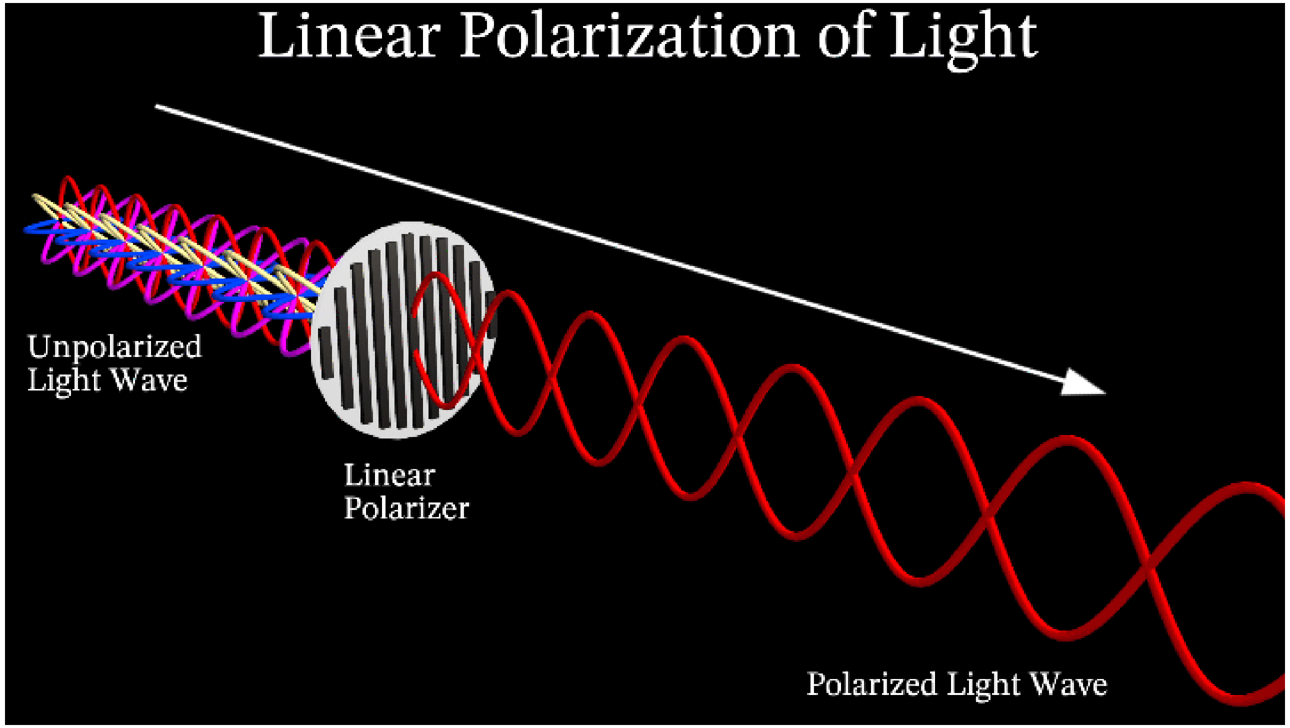


unpolarized

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

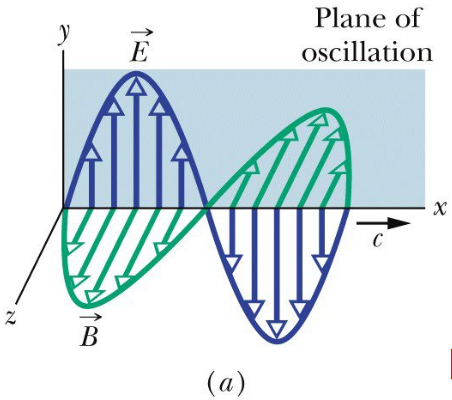
33-4 Polarization (极化)(3 of 4)

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

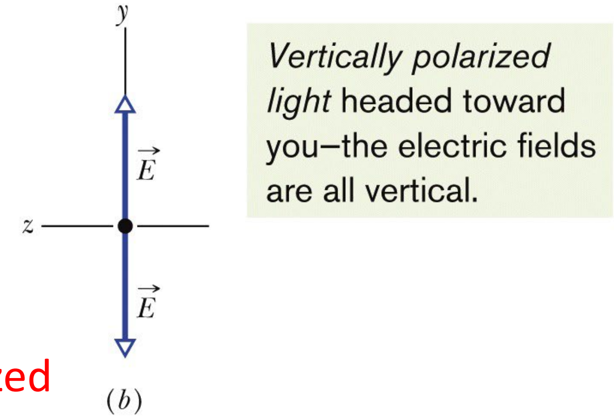


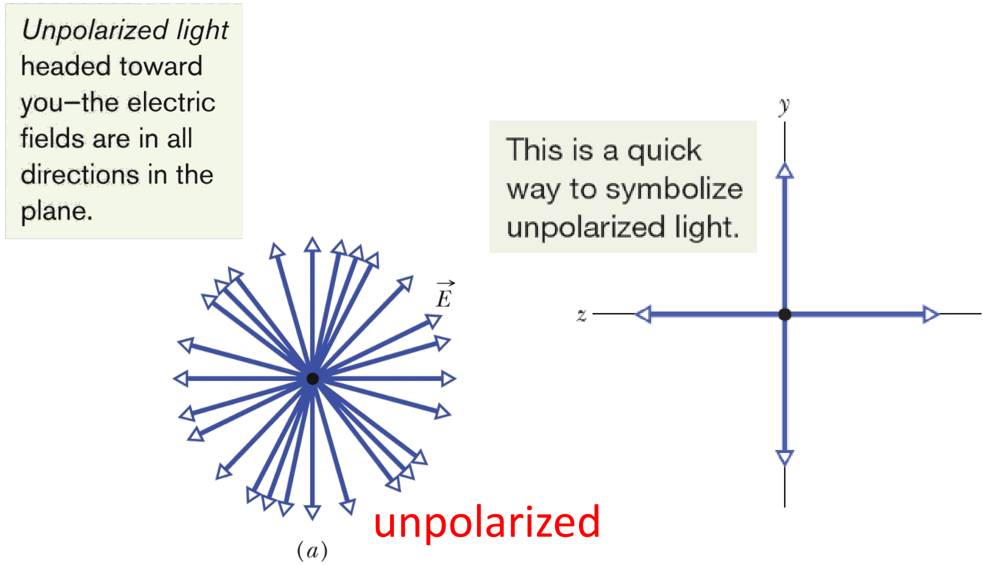
33-4 Polarization (极化)(3 of 4)

Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation. Light waves from common sources are not polarized; that is, they are unpolarized, or polarized randomly.



polarized





unpolarized

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

33-4 Polarization (4 of 4)

If the original light is initially unpolarized, the transmitted intensity I is half the original intensity I_0:

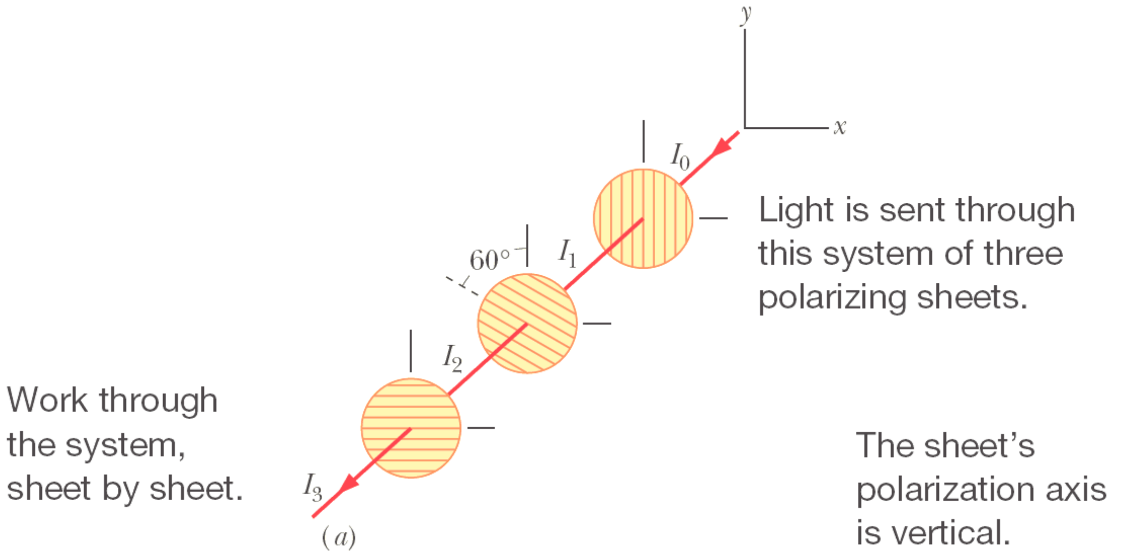
$$I = \frac{1}{2} I_0 \qquad \text{(one-half rule)}.$$

If the original light is initially polarized, the transmitted intensity depends on the angle between the polarization direction of the original light and the polarizing direction of the sheet:

$$I = I_0 \cos^2\theta \qquad \text{(cosine-squared rule)}.$$

33-4 Polarization (4 of 4)

Figure 33-15*a*, drawn in perspective, shows a system of three polarizing sheets in the path of initially unpolarized light. The polarizing direction of the first sheet is parallel to the y axis, that of the second sheet is at an angle of 60° counterclockwise from the y axis, and that of the third sheet is parallel to the x axis. What fraction of the initial intensity I_0 of the light emerges from the three-sheet system, and in which direction is that emerging light polarized?



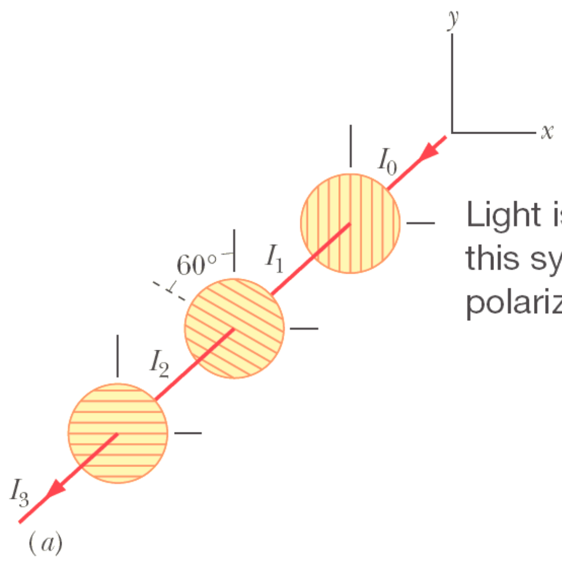
(*a*)

$$I = \frac{1}{2} I_0 \qquad \text{(one-half rule).}$$

$$I = I_0 \cos^2\theta \qquad \text{(cosine-squared rule).}$$

33-4 Polarization (4 of 4)

Figure 33-15a, drawn in perspective, shows a system of three polarizing sheets in the path of initially unpolarized light. The polarizing direction of the first sheet is parallel to the y axis, that of the second sheet is at an angle of 60° counterclockwise from the y axis, and that of the third sheet is parallel to the x axis. What fraction of the initial intensity I_0 of the light emerges from the three-sheet system, and in which direction is that emerging light polarized?



Light is sent through this system of three polarizing sheets.

Work through the system, sheet by sheet.

The sheet's polarization axis is vertical.

Second sheet: ***θ* is 60°** $I_2 = I_1 \cos^2 60°.$

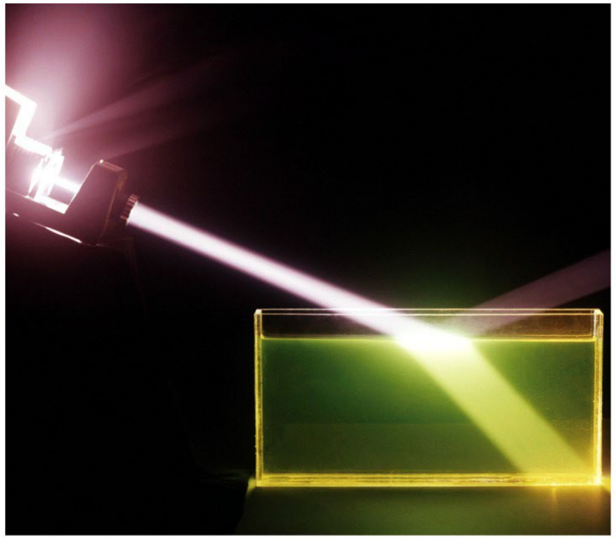
$$I_3 = I_2 \cos^2 30° = (I_1 \cos^2 60°) \cos^2 30°$$

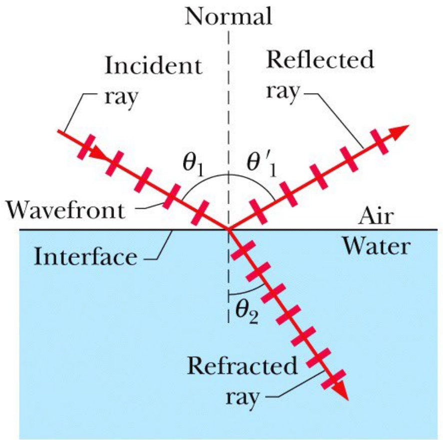
Third sheet ***θ* is 30°** $I_3 = I_2 \cos^2 30°.$

$$= (\tfrac{1}{2} I_0) \cos^2 60° \cos^2 30° = 0.094 I_0.$$

9.4% of the initial intensity emerges from the three-sheet system

33-5 Reflection and Refraction (4 of 11)


(a)



(b)

When a light ray encounters a boundary between two transparent media, a reflected ray and a refracted ray generally appear as shown in figure

(a) A photograph showing an incident beam of light reflected and refracted by a horizontal water surface.

(b) A ray representation of (a). The angles of incidence (θ_1), reflection (θ_1'), and refraction (θ_2) are marked.

33-5 Reflection and Refraction (5 of 11)

Law of reflection: A reflected ray lies in the plane of incidence and has an angle of reflection equal to the angle of incidence (both relative to the normal). In Fig. (b), this means that

$$\theta_1' = \theta_1 \qquad (\text{reflection}).$$

33-5 Reflection and Refraction

Law of refraction: A refracted ray lies in the plane of incidence and has an angle of refraction θ_2 that is related to the angle of incidence θ_1 by

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

Here each of the symbols n_1 and n_2 is a dimensionless constant, called the **index of refraction 折射率**, that is associated with a medium involved in the refraction.

33-5 Reflection and Refraction (7 of 11)

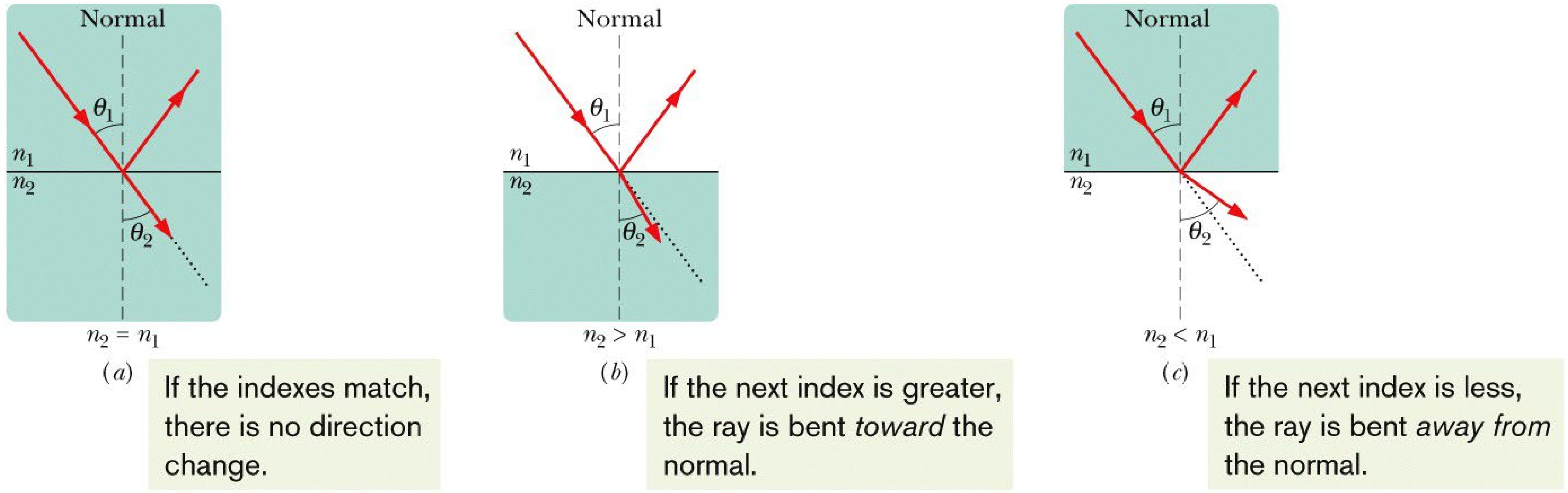
Table 33-1 Some Indexes of Refraction[a]

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)."

33-5 Reflection and Refraction (8 of 11)



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

33-5 Reflection and Refraction (9 of 11)

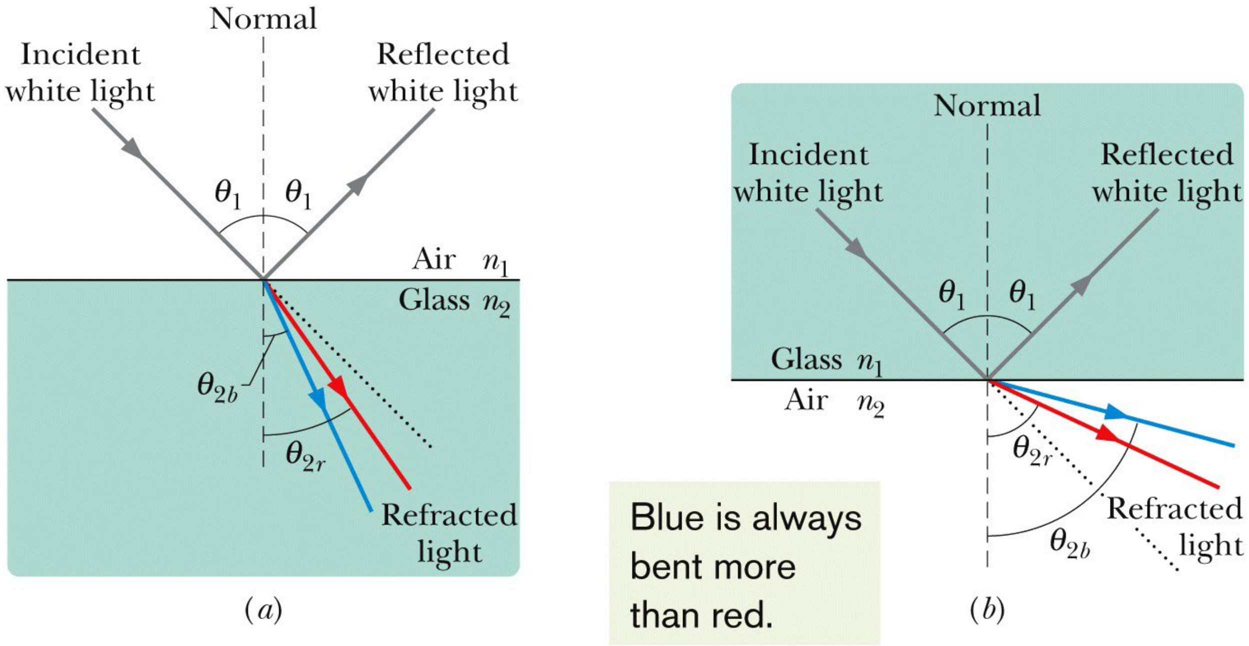
1. If n_2 is equal to n_1, then θ_2 is equal to θ_1 and refraction does not bend the light beam, which continues in the undeflected direction, as in Figure (a).

2. If n_2 is greater than n_1, then θ_2 is less than θ_1. In this case, refraction bends the light beam away from the undeflected direction and toward the normal, as in Figure (b).

3. If n_2 is less than n_1, then θ_2 is greater than θ_1. In this case, refraction bends the light beam away from the undeflected direction and away from the normal, as in Figure (c).

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

33-5 Reflection and Refraction (10 of 11)



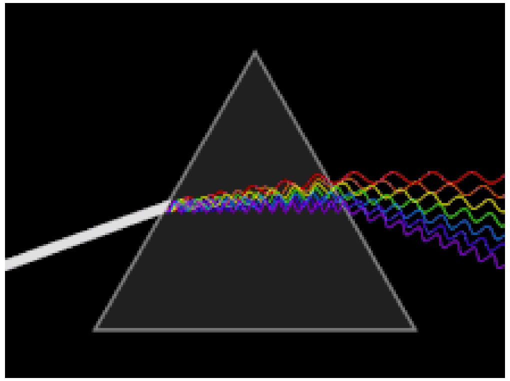
Chromatic dispersion **色散** of white light. The blue component is bent more than the red component.

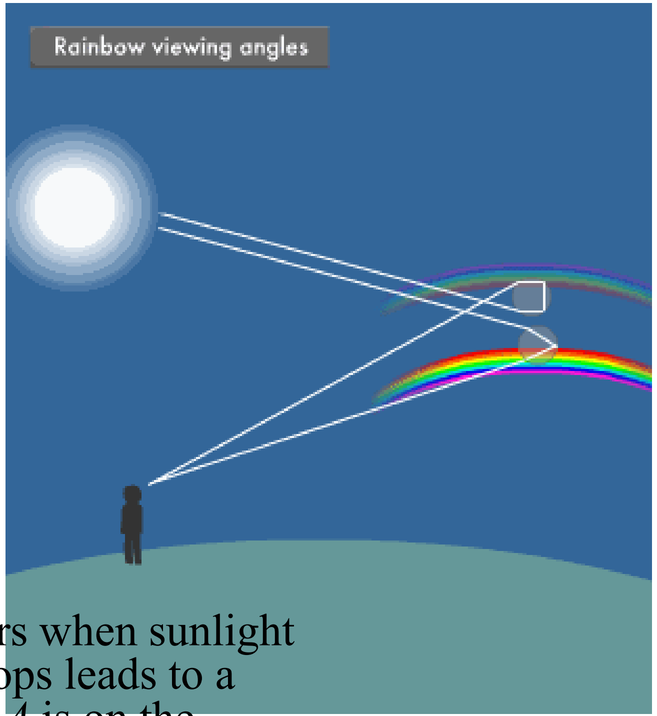
(a) Passing from air to glass, the blue component ends up with the smaller angle of refraction.

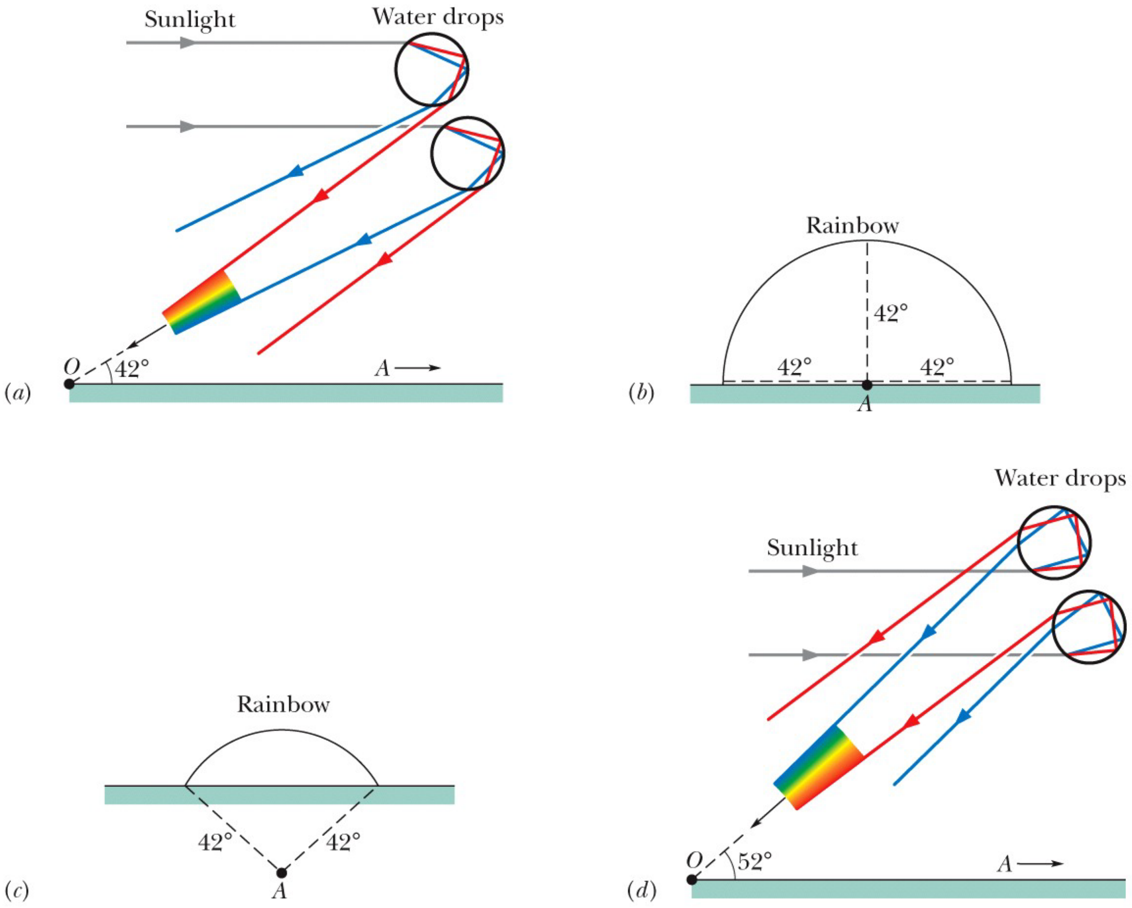
(b) Passing from glass to air, the blue component ends up with the greater angle of refraction.

Each dotted line represents the direction in which the light would continue to travel if it were not bent by the refraction.

33-5 Reflection and Refraction



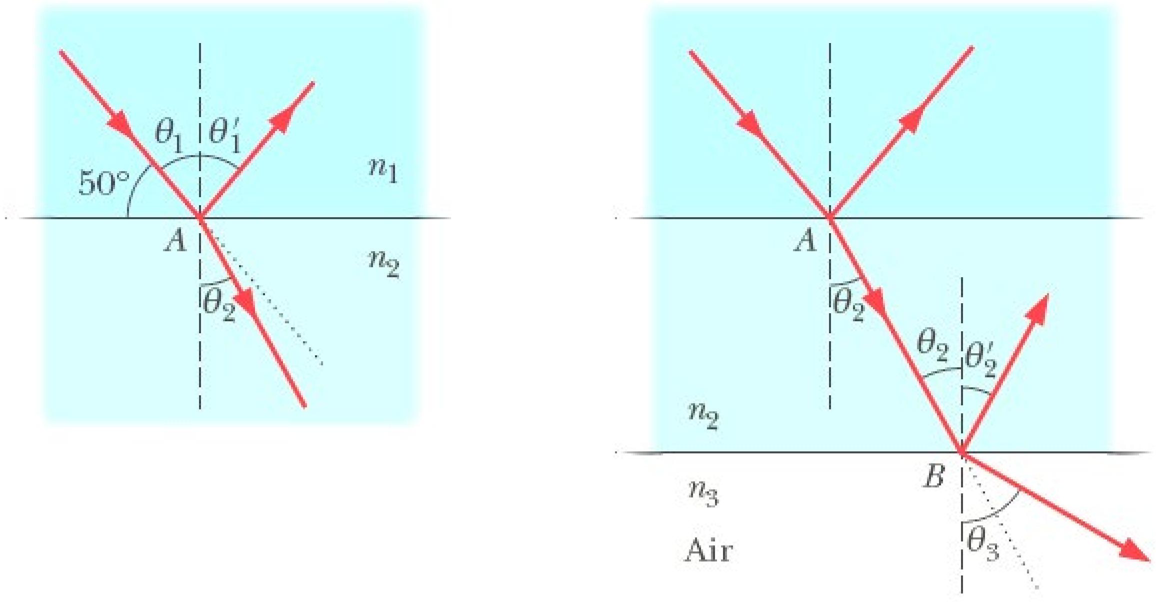




Rainbow: (a) The separation of colors when sunlight refracts into and out of falling raindrops leads to a primary rainbow. The antisolar point *A* is on the horizon at the right. The rainbow colors appear at an angle of 42° from the direction of *A*. (b) Drops at 42° from *A* in any direction can contribute to the rainbow. (c) The rainbow arc when the Sun is higher (and thus *A* is lower). (d) The separation of colors leading to a secondary rainbow.

33-5 Reflection and Refraction (11 of 11)

(a) In Fig. 33-22*a*, a beam of monochromatic light reflects and refracts at point *A* on the interface between material 1 with index of refraction n_1 = 1.33 and material 2 with index of refraction n_2 = 1.77. The incident beam makes an angle of 50° with the interface. What is the angle of reflection at point *A*? What is the angle of refraction there?



(*a*) (*b*)

33-5 Reflection and Refraction (11 of 11)

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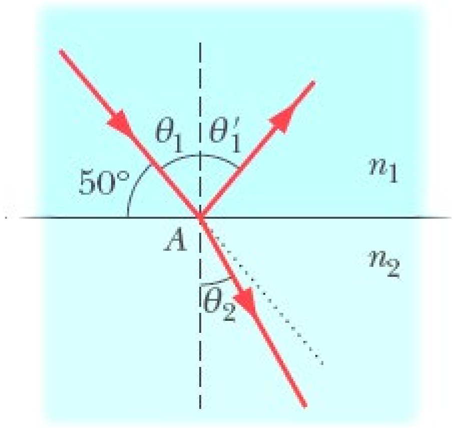
$$n_2 \sin \theta_2 = n_1 \sin \theta_1,$$

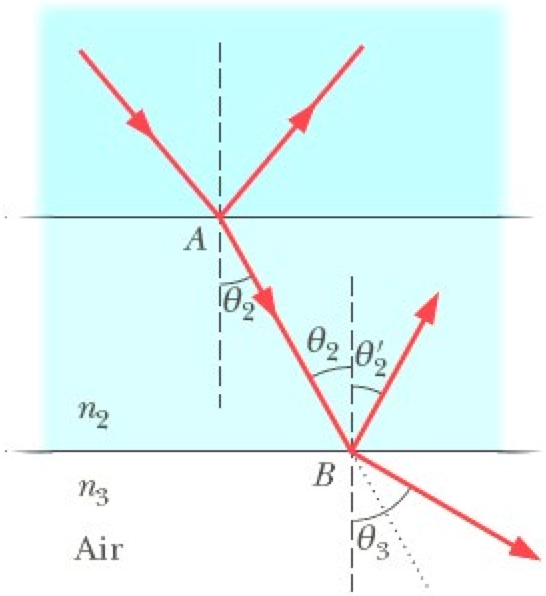
$$\theta'_1 = \theta_1 = 40°.$$

$$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin \theta_1\right) = \sin^{-1}\left(\frac{1.33}{1.77}\sin 40°\right)$$

$$= 28.88° \approx 29°. \qquad \text{(Answer)}$$



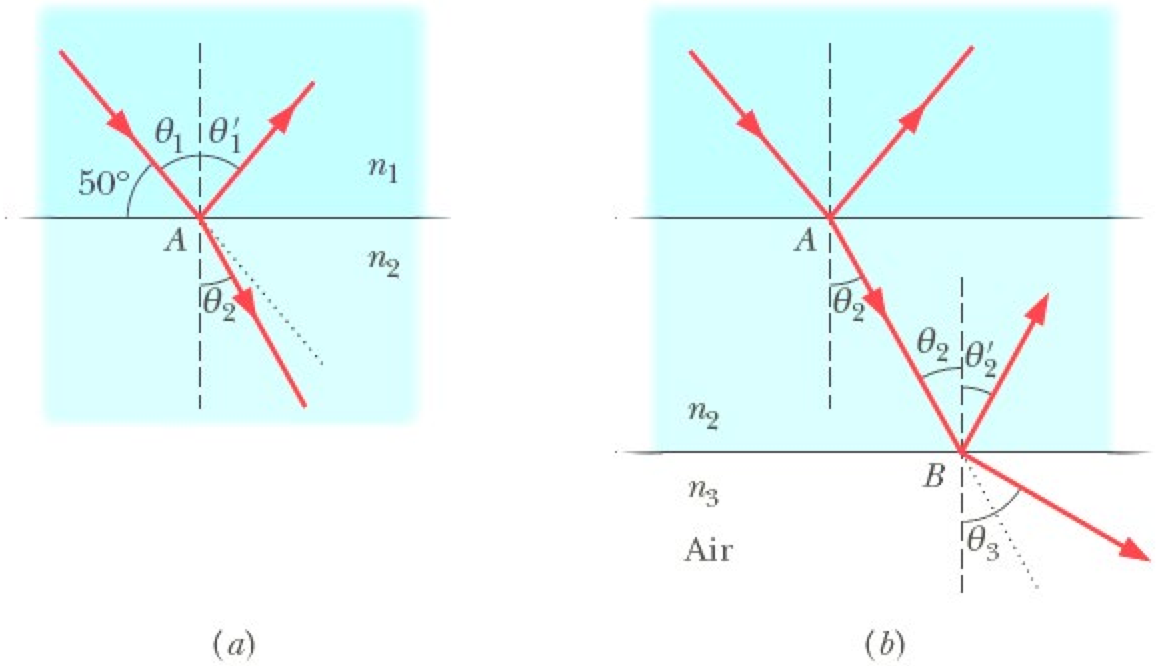
(*a*)



(*b*)

33-5 Reflection and Refraction (11 of 11)

(b) The light that enters material 2 at point A then reaches point B on the interface between material 2 and material 3, which is air, as shown in Fig. b. The interface through B is parallel to that through A. At B, some of the light reflects and the rest enters the air. What is the angle of reflection? What is the angle of refraction into the air?



33-5 Reflection and Refraction (11 of 11)

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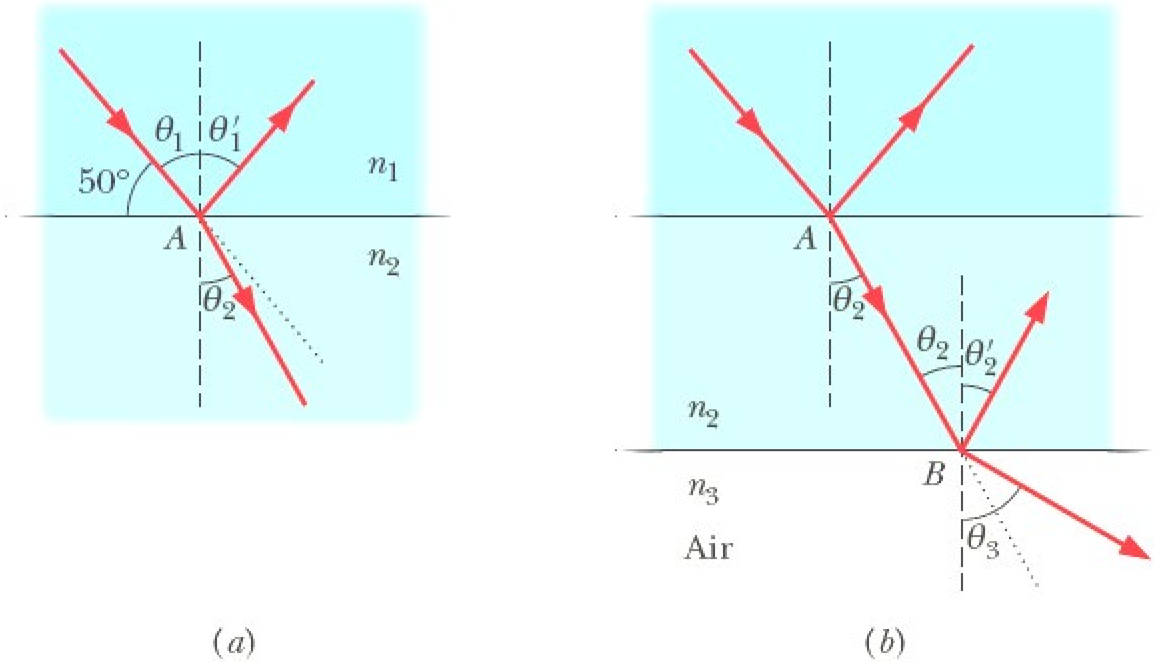
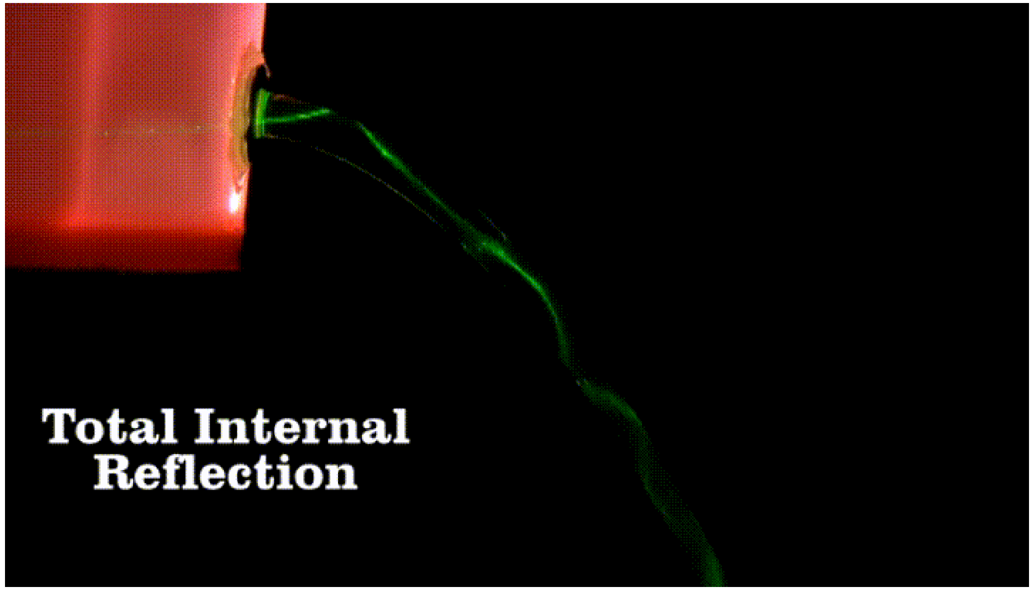
$$\theta'_2 = \theta_2 = 28.88° \approx 29°$$

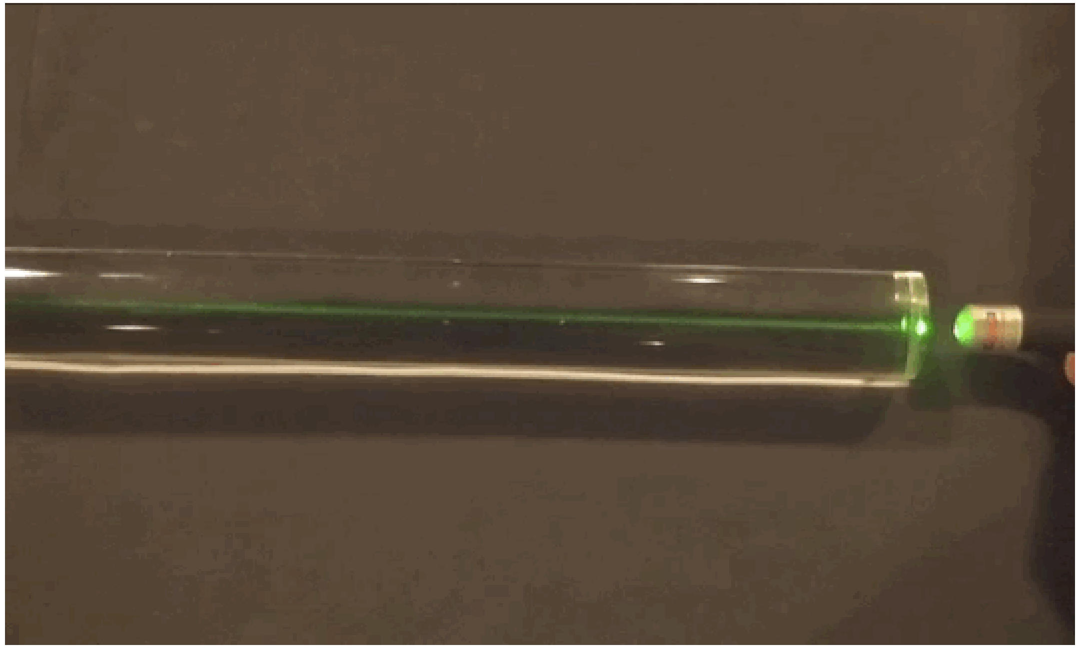
$$\theta_3 = \sin^{-1}\left(\frac{n_2}{n_3}\sin\theta_2\right) = \sin^{-1}\left(\frac{1.77}{1.00}\sin 28.88°\right)$$
$$= 58.75° \approx 59°. \qquad \text{(Answer)}$$



33-6 Total Internal Reflection 全内反射 (2 of 3)

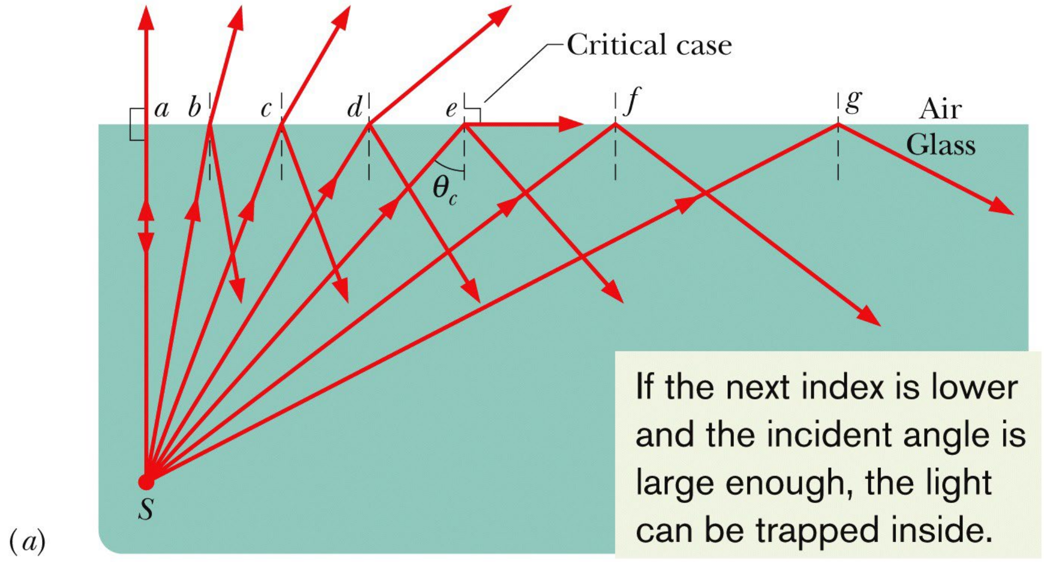


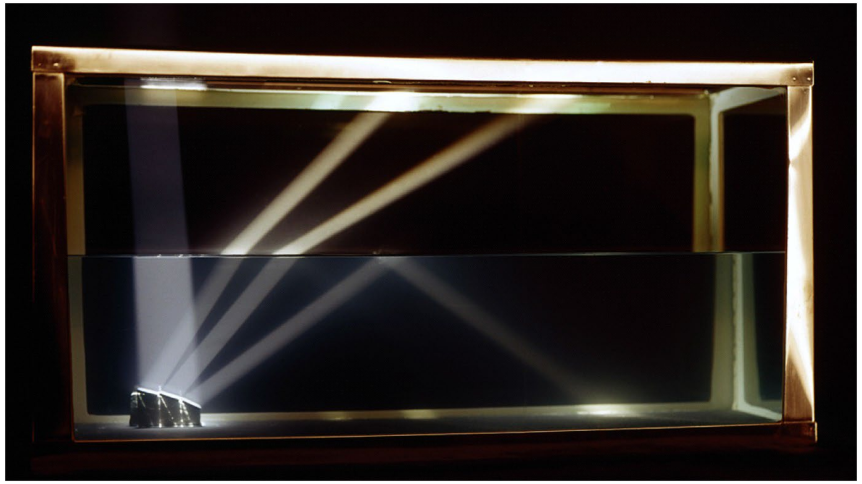
Laser Light Flowing Along a Liquid Stream
Due to Total Internal Reflection



Total Internal Reflection In Optical Fiber 光纤

33-6 Total Internal Reflection 全内反射 (2 of 3)





Ken Kay/Fundamental Photographs

(a) Total internal reflection of light from a point source S in glass occurs for all angles of incidence greater than the critical angle θ_c. At the critical angle临界角, the refracted ray points along the air – glass interface. (b) A source in a tank of water.

33-6 Total Internal Reflection (3 of 3)

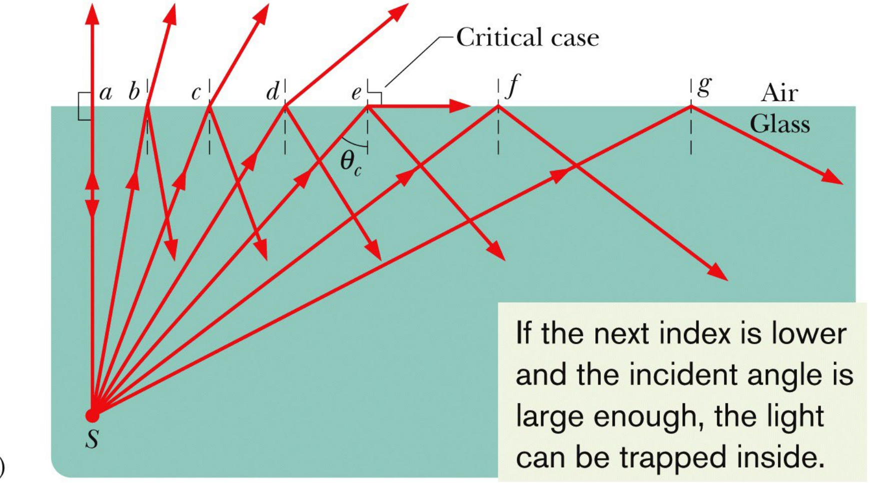


Figure (a) shows rays of monochromatic light from a point source S in glass incident on the interface between the glass and air.

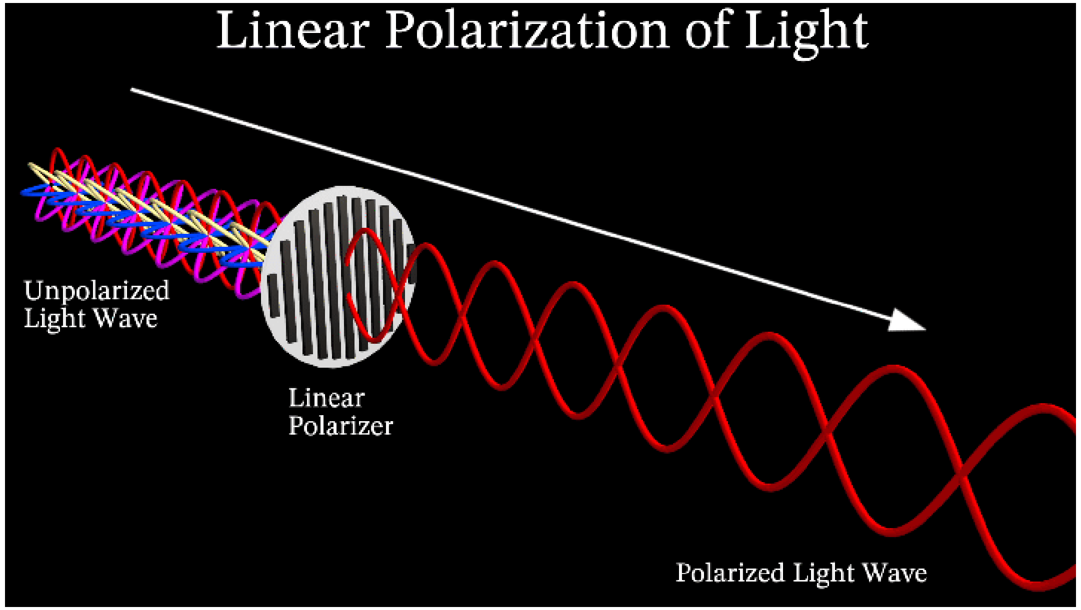
For ray a, which is perpendicular to the interface, part of the light reflects at the interface and the rest travels through it with no change in direction.

For rays b through e, which have progressively larger angles of incidence at the interface, there are also both reflection and refraction at the interface. As the angle of incidence increases, the angle of refraction increases;

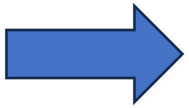
for ray e it is 90°, which means that the refracted ray points directly along the interface. The angle of incidence giving this situation is called the **critical angle** θ_c.

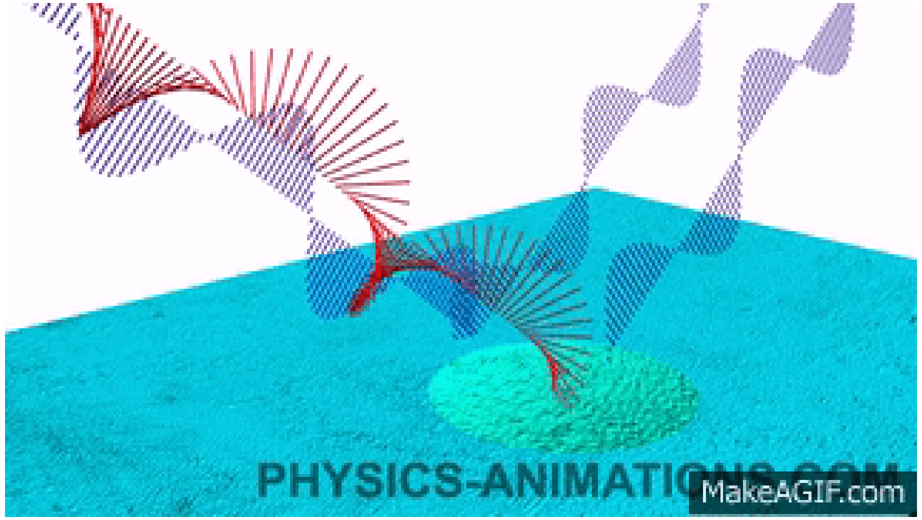
For angles of incidence larger than θ_c, such as for rays f and g, there is no refracted ray and all the light is reflected; this effect is called **total internal reflection** because all the light remains inside the glass.

33-7 Polarization by Reflection (2 of 3)



Polarization by transition





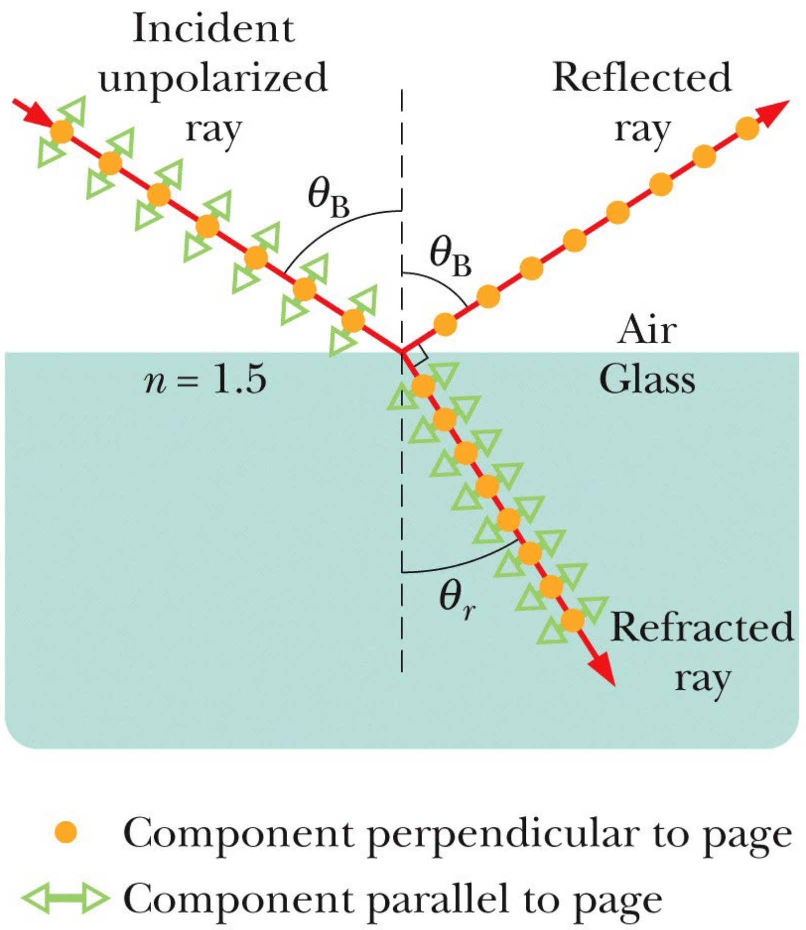
Polarization by Reflection

33-7 Polarization by Reflection (2 of 3)

A ray of unpolarized light in air is incident on a glass surface at the 布儒斯特角 **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.



33-7 Polarization by Reflection (3 of 3)

As shown in the figure above a reflected wave will be fully polarized, with its ***E*** vectors perpendicular to the plane of incidence, if it strikes a boundary at the Brewster angle θ_B,

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

Summary (1 of 7)

Electromagnetic Waves

- An electromagnetic wave consists of oscillating electric and magnetic fields as given by,

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

Equation 33-1

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

Equation 33-2

- The speed of any electromagnetic wave in vacuum is c, which can be written as

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

Equation 33-5 & 3

Summary (2 of 7)

Energy Flow

- The rate per unit area at which energy is trans- ported via an electromagnetic wave is given by the Poynting vector $\vec{S}$:

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}.$$

Equation 33-19

- The intensity I of the wave is:

$$I = \frac{1}{c\mu_0}E_{\text{rms}}^2$$

Equation 33-26

Summary (3 of 7)

- The intensity of the waves at distance r from a point source of power P_s is

$$I = \frac{P_s}{4\pi r^2}.$$

Equation 33-27

Radiation Pressure

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{IA}{c}$$

Equation 33-32

Summary (4 of 7)

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{2IA}{c}$$

Equation 33-33

Radiation Pressure

- The radiation pressure p_r is the force per unit area.
- For total absorption

$$p_r = \frac{I}{c}$$

Equation 33-34

- For total reflection back along path,

$$p_r = \frac{2I}{c}$$

Equation 33-35

Summary (5 of 7)

Polarization

- Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation.
- If the original light is initially unpolarized, the transmitted intensity *I* is

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

Equation 33-36

- If the original light is initially polarized, the transmitted intensity depends on the angle u between the polarization direction of the original light (the axis along which the fields oscillate) and the polarizing direction of the sheet:

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

Equation 33-26

Summary (6 of 7)

Reflection and Refraction

- The angle of reflection is equal to the angle of incidence, and the angle of refraction is related to the angle of incidence by Snell's law,

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

Equation 33-40

Total Internal Reflection

- A wave encountering a boundary across which the index of refraction decreases will experience total internal reflection if the angle of incidence exceeds a critical angle,

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

Equation 33-45

Summary (7 of 7)

Polarization by Reflection

- A reflected wave will be fully polarized, if the incident, unpolarized wave strikes a boundary at the Brewster angle

$$\theta_B = \tan^{-1}\frac{n_2}{n_1}$$

Equation 33-49

33.2.2. For which one of the following properties do visible light and ultraviolet waves have the same value?

a) wavelength

b) frequency

c) speed

d) energy

e) period

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a) wavelength

b) frequency

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d) energy

e) period

33.5.3. The intensity of electromagnetic wave A is one fourth that of wave B. How does the magnitude of the electric field of wave A compare to that of wave B?

a) The electric field amplitude of wave A is one fourth that of wave B.

b) The electric field amplitude of wave A is one half that of wave B.

c) The electric field amplitude of wave A is two times that of wave B.

d) The electric field amplitude of wave A is four times that of wave B.

$$I = \frac{1}{c\mu_0} E_{\text{rms}}^2 \qquad I = \frac{P_s}{4\pi r^2}.$$

33.5.3. The intensity of electromagnetic wave A is one fourth that of wave B. How does the magnitude of the electric field of wave A compare to that of wave B?

a) The electric field amplitude of wave A is one fourth that of wave B.

b) The electric field amplitude of wave A is one half that of wave B.

c) The electric field amplitude of wave A is two times that of wave B.

d) The electric field amplitude of wave A is four times that of wave B.

33.6.1. In which of the following cases is the largest force exerted on an object by electromagnetic radiation?

a) The radiation is absorbed by the object.

b) Nearly all of the radiation is transmitted through the object because it is transparent.

c) The radiation strikes the surface at a large angle with respect to the normal to the surface.

d) The radiation is reflected back along its incident path.

e) In all of the above cases the force will be the same since it is the same light striking the object.

33.6.1. In which of the following cases is the largest force exerted on an object by electromagnetic radiation?

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e) In all of the above cases the force will be the same since it is the same light striking the object.

33.7.3. Unpolarized light of intensity S is directed toward three polarizing sheets. The first sheet is polarized vertically; and the last sheet is oriented horizontally. If the middle sheet is also oriented vertically, what is the intensity of the light exiting the last polarizer?

a) zero

b) $0.25S$

c) $0.5S$

d) $0.71S$

e) S

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

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

33.7.3. Unpolarized light of intensity S is directed toward three polarizing sheets. The first sheet is polarized vertically; and the last sheet is oriented horizontally. If the middle sheet is also oriented vertically, what is the intensity of the light exiting the last polarizer?

a) zero

b) $0.25S$

c) $0.5S$

d) $0.71S$

e) S

Summary (3 of 9)

Maxwell's Equations

- Four equations are as follows:

$$\oint \vec{E} \cdot d\vec{A} = \frac{q_{enc}}{\varepsilon_0}$$

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

$$\oint \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_B}{dt} + \mu_0 i_{\text{enc}}$$

电磁学的基本规律是真空中的电磁场规律，它们是

$$\text{I} \quad \oint_S \boldsymbol{E} \cdot \mathrm{d}\boldsymbol{S} = \frac{q}{\varepsilon_0} = \frac{1}{\varepsilon_0}\int_V \rho \mathrm{d}V$$

$$\text{II} \quad \oint_S \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{S} = 0$$

$$\text{III} \quad \oint_L \boldsymbol{E} \cdot \mathrm{d}\boldsymbol{r} = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -\int_S \frac{\partial \boldsymbol{B}}{\partial t} \cdot \mathrm{d}\boldsymbol{S}$$

$$\text{IV} \quad \oint_L \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{r} = \mu_0 I + \boxed{\frac{1}{c^2}\frac{\mathrm{d}\Phi_e}{\mathrm{d}t}} = \mu_0 \int_S \left(\boldsymbol{J} + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}\right) \cdot \mathrm{d}\boldsymbol{S}$$

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

Summary (3 of 9)

磁学的基本规律是真空中的电磁场规律，它们是

$$\text{I} \quad \oint_S \boldsymbol{E}\cdot \mathrm{d}\boldsymbol{S} = \frac{q}{\varepsilon_0} = \frac{1}{\varepsilon_0}\int_V \rho \mathrm{d}V$$

$$\text{II} \quad \oint_S \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{S} = 0$$

$$\text{III} \quad \oint_L \boldsymbol{E}\cdot \mathrm{d}\boldsymbol{r} = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -\int_S \frac{\partial \boldsymbol{B}}{\partial t}\cdot \mathrm{d}\boldsymbol{S}$$

$$\text{IV} \quad \oint_L \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{r} = \mu_0 I + \frac{1}{c^2}\frac{\mathrm{d}\Phi_e}{\mathrm{d}t} = \mu_0\int_S\left(\boldsymbol{J} + \varepsilon_0\frac{\partial \boldsymbol{E}}{\partial t}\right)\cdot \mathrm{d}\boldsymbol{S}$$

在有介质的情况下，利用辅助量 $\boldsymbol{D}$ 和 $\boldsymbol{H}$，麦克斯韦方程组的积分形式如下：

$$\text{I}' \quad \oint_S \boldsymbol{D}\cdot \mathrm{d}\boldsymbol{S} = \int_V \rho \mathrm{d}V$$

$$\text{II}' \quad \oint_S \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{S} = 0$$

$$\text{III}' \quad \oint_L \boldsymbol{E}\cdot \mathrm{d}\boldsymbol{r} = -\int_S \frac{\partial \boldsymbol{B}}{\partial t}\cdot \mathrm{d}\boldsymbol{S}$$

$$\text{IV}' \quad \oint_L \boldsymbol{H}\cdot \mathrm{d}\boldsymbol{r} = \int_S\left(\boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}\right)\cdot \mathrm{d}\boldsymbol{S}$$

利用数学上关于矢量运算的定理，上述方程组还可以变化为如下微分形式

$$\text{I}'' \quad \nabla\cdot\boldsymbol{D} = \rho$$

$$\text{II}'' \quad \nabla\cdot\boldsymbol{B} = 0$$

$$\text{III}'' \quad \nabla\times\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\text{IV}'' \quad \nabla\times\boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

梯度（▽z）、散度（▽·E）和旋度（▽×E）

$$\nabla = \frac{\partial}{\partial x}\vec{x} + \frac{\partial}{\partial y}\vec{y}$$

对于各向同性的线性介质，下述关系成立：

$$\boldsymbol{D} = \varepsilon_0\varepsilon_r\boldsymbol{E}, \quad \boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}, \quad \boldsymbol{J} = \sigma\boldsymbol{E}$$

Summary (3 of 9)

1.1 在正交曲线坐标系(u_1, u_2, u_3)中，梯度、散度和旋度的表达式分别为

$$\nabla\phi = \frac{1}{h_1}\frac{\partial\phi}{\partial u_1}e_1 + \frac{1}{h_2}\frac{\partial\phi}{\partial u_2}e_2 + \frac{1}{h_3}\frac{\partial\phi}{\partial u_3}e_3$$

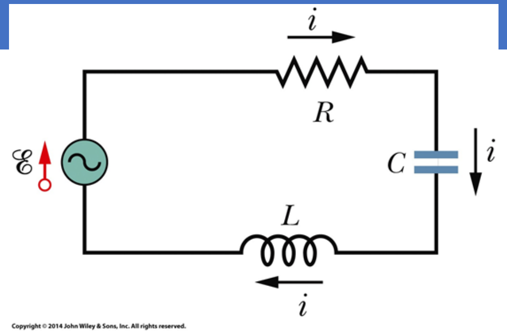
$$\nabla\cdot A = \frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial u_1}(h_2h_3A_1) + \frac{\partial}{\partial u_2}(h_3h_1A_2) + \frac{\partial}{\partial u_3}(h_1h_2A_3)\right]$$

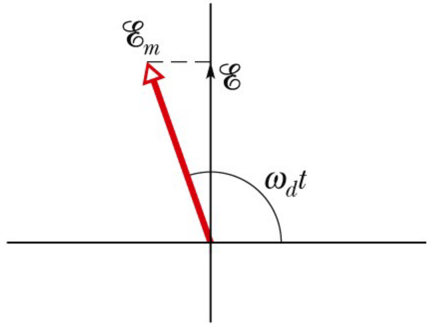
$$\nabla\times A = \frac{1}{h_2h_3}\left[\frac{\partial}{\partial u_2}(h_3A_3) - \frac{\partial}{\partial u_3}(h_2A_2)\right]e_1 + \frac{1}{h_3h_1}\left[\frac{\partial}{\partial u_3}(h_1A_1) - \frac{\partial}{\partial u_1}(h_3A_3)\right]e_2$$

$$+ \frac{1}{h_1h_2}\left[\frac{\partial}{\partial u_1}(h_2A_2) - \frac{\partial}{\partial u_2}(h_1A_1)\right]e_3$$

式中e_1、e_2和e_3为正交曲线坐标系的三个基矢；h_1、h_2和h_3为标度因子(scale factor)，或拉梅(Lamé)系数；ϕ为空间的标量函数，A为空间的矢量函数.

31-4 The Series RLC Circuits (7 of 7)

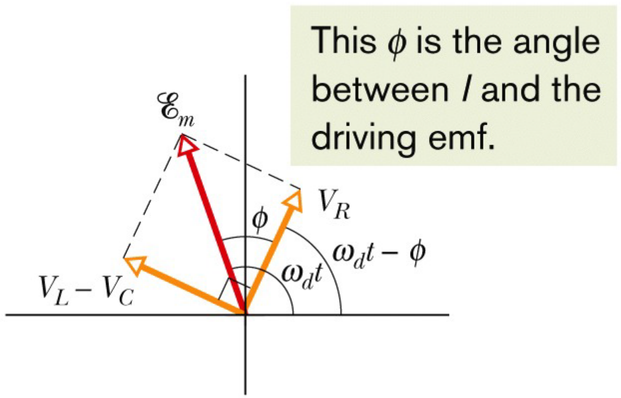




(c)

From the right-hand phasor triangle in Figure (d) we can write

$$\tan\phi = \frac{V_L - V_C}{V_R} = \frac{IX_L - IX_C}{IR}, \quad \Rightarrow \quad \tan\phi = \frac{X_L - X_C}{R}$$ **Phase Constant**



(d)

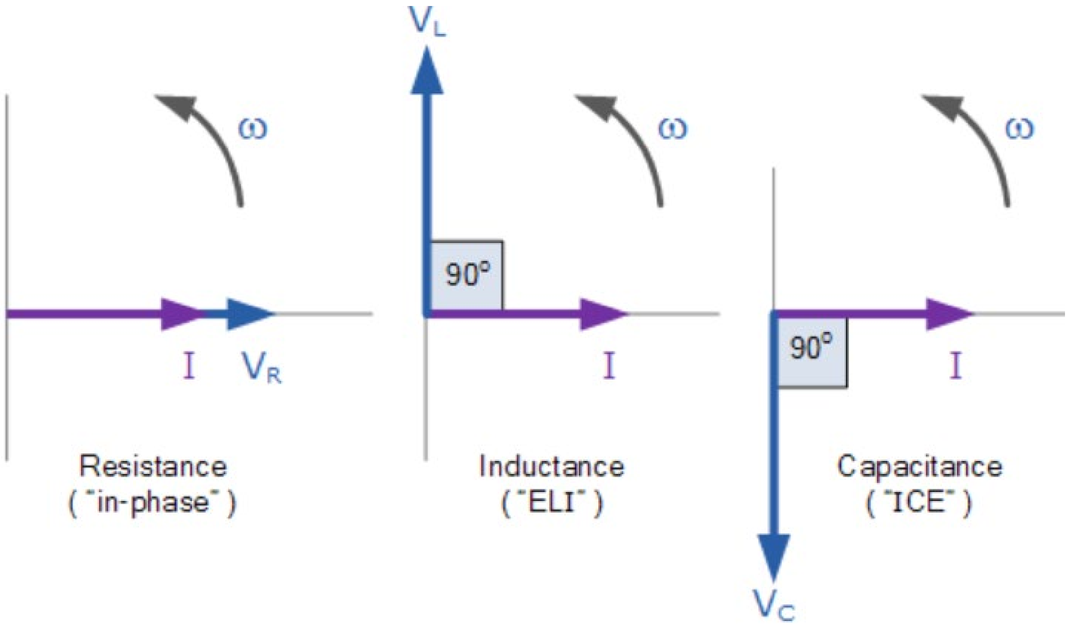
phasor diagram

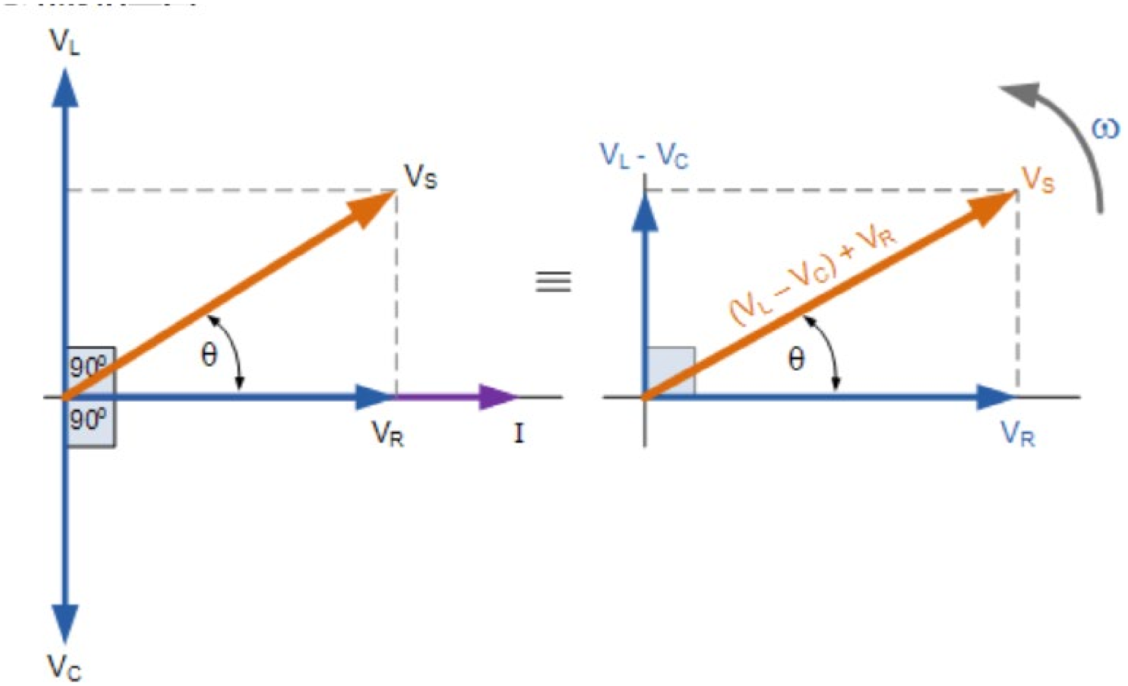
The current amplitude I is maximum when the driving ω angular frequency ω_d equals the natural angular frequency of the circuit, a condition known as **resonance**. Then $X_C = X_L$, $\phi = 0$, and the current is in phase with the emf.

$$\omega_d = \omega = \frac{1}{\sqrt{LC}} \quad \text{(resonance)}.$$

Summary (3 of 9)

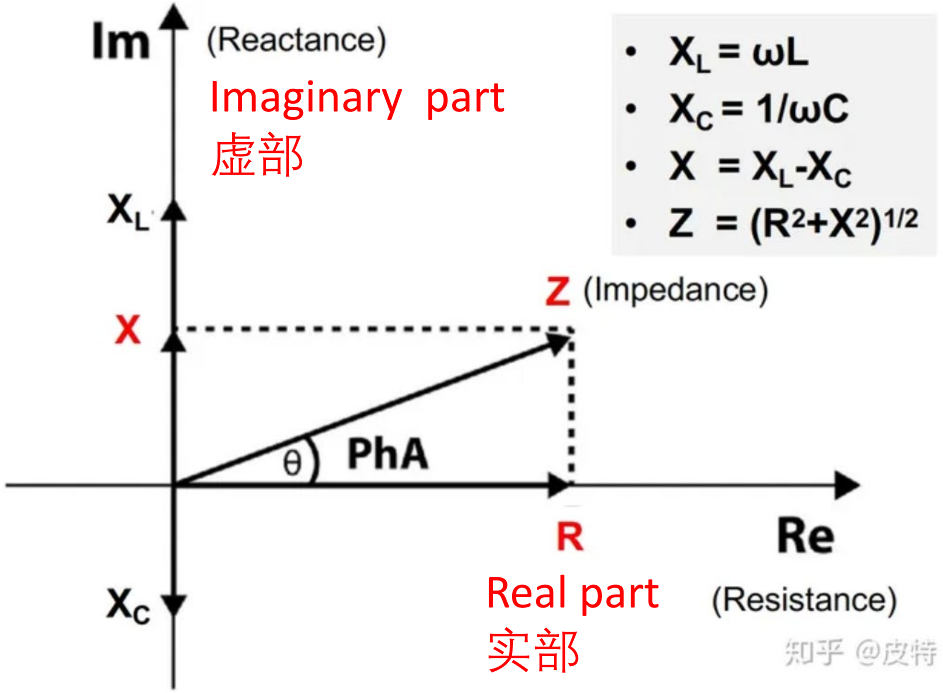
phasor diagram





Summary (3 of 9)

Impedance diagram



- $X_L = \omega L$
- $X_C = 1/\omega C$
- $X = X_L - X_C$
- $Z = (R^2+X^2)^{1/2}$

$Z=R+Xi$