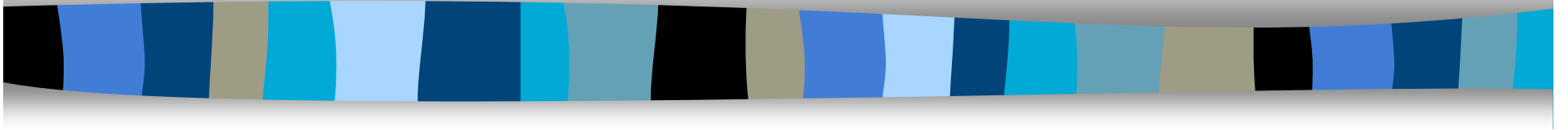


Chapter 23 - Electromagnetic waves





reading quiz

- Which wave travels fastest in a vacuum
 - *A. X-rays*
 - *B. Gamma Rays*
 - *C. Visible Light*
 - *D. All travel at the same speed*

- In an electromagnetic wave which of the following is true
 - *A. E and B fields are perpendicular*
 - *B. E and B fields are parallel*
 - *C. E-field is always zero*
 - *D. B-field points along the direction of propagation*



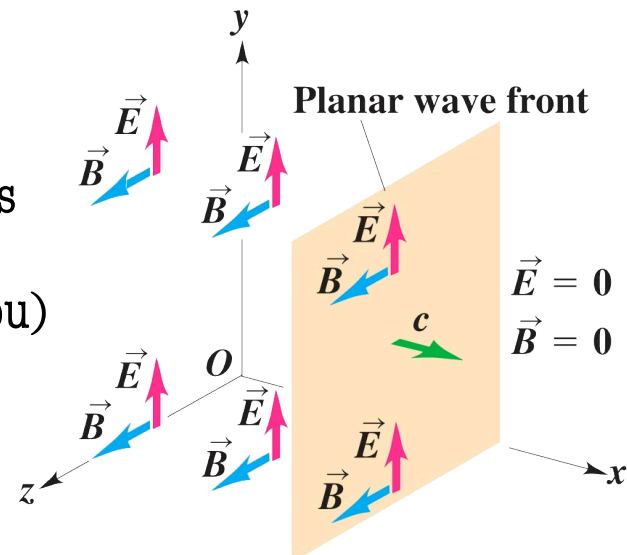
electromagnetic waves?

- Faraday's law told us that
 - *time-varying magnetic fields generate electric fields*
- James Clerk Maxwell found that
 - *time-varying electric fields generate magnetic fields*
- taken together then
 - *electric field* → *magnetic field* → *electric field* → ...
- with this we can have *disturbances* in the electric and magnetic fields that *propagate across space*
 - *ELECTROMAGNETIC WAVES*
- unlike the waves you met in Phys111, such as sound waves or waves on a string, no *medium* is required - it is not atoms moving around, but instead the electric and magnetic fields and these can exist even in a vacuum

speed of electromagnetic waves?

- simple em wave:
 - electric field in the y -direction
 - magnetic field in the z -direction
 - propagation in the x -direction, with unknown speed, c
- turns out this satisfies the equations of electromagnetism (Faraday's law and some others I haven't shown you)
- but *only if* $E = cB$
- and $c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$
- so $c = 3.00 \times 10^8 \text{ m/s}$
- experiments with mirrors and long distances indicate that the speed of light (in vacuum, strictly) also has this value

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



– LIGHT IS AN ELECTROMAGNETIC WAVE

properties of electromagnetic waves?

- we considered a very simple em wave, there are many more possibilities, but they all have certain common properties:
 - they are *transverse*: \vec{E} and \vec{B} are perpendicular to each other and to the direction of motion
 - the ratio of magnitudes of electric and magnetic fields are fixed

$$\frac{E}{B} = c$$

- wave travels with a fixed speed (in vacuum)

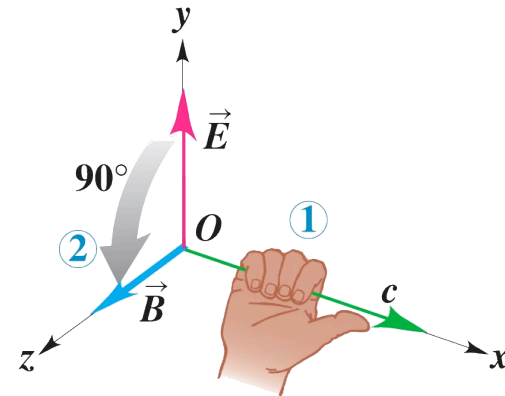
$$c = 3.00 \times 10^8 \text{ m/s}$$

- no medium is required for 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.





speed of light (in vacuum)

- how much time is required for light to travel 1 foot ?

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

$$1 \text{ ft} = 0.305 \text{ m}$$

$$t = \frac{x}{v} = \frac{0.305 \text{ m}}{3.00 \times 10^8 \text{ m/s}} = 1.02 \text{ ns}$$

the electromagnetic spectrum

- from the speed of electromagnetic waves being equal to the measured speed of visible light, we guess that visible light is an em wave
- but so are a lot of other waves that we often think of as being 'different' from visible light
- they actually only differ in their frequency (or wavelength)

$$c = f\lambda$$

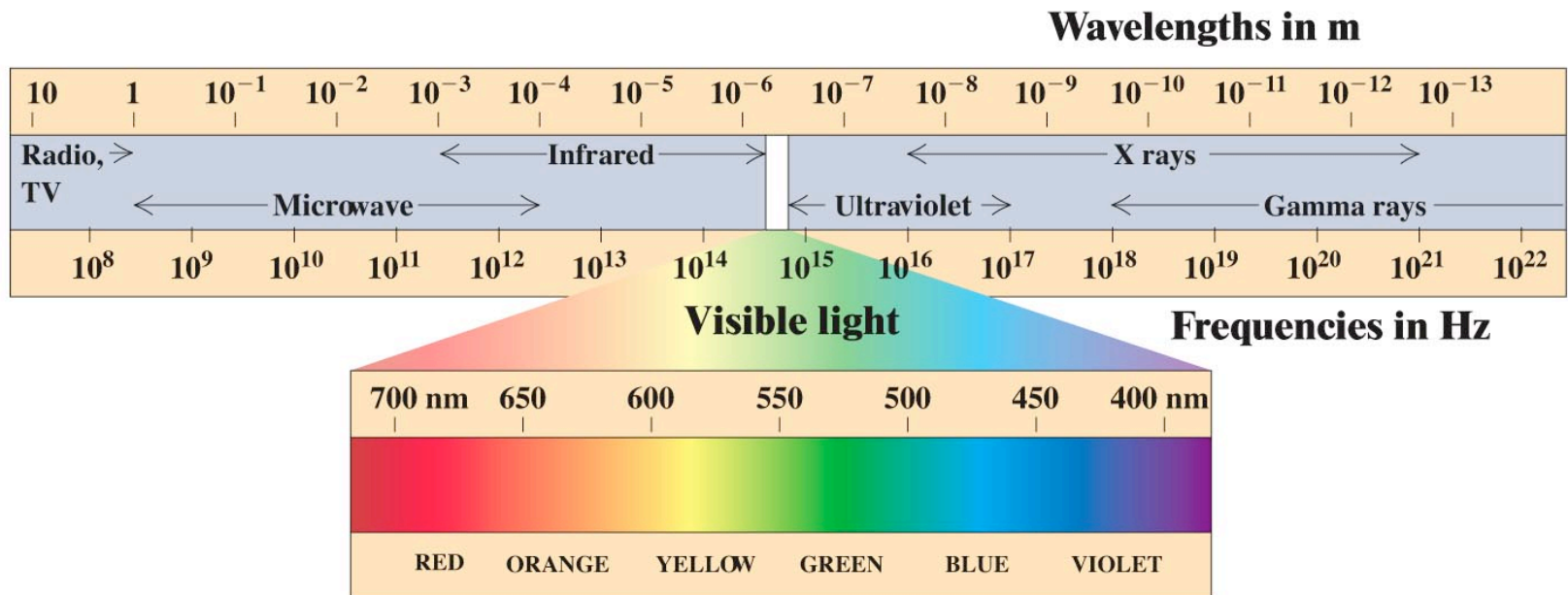
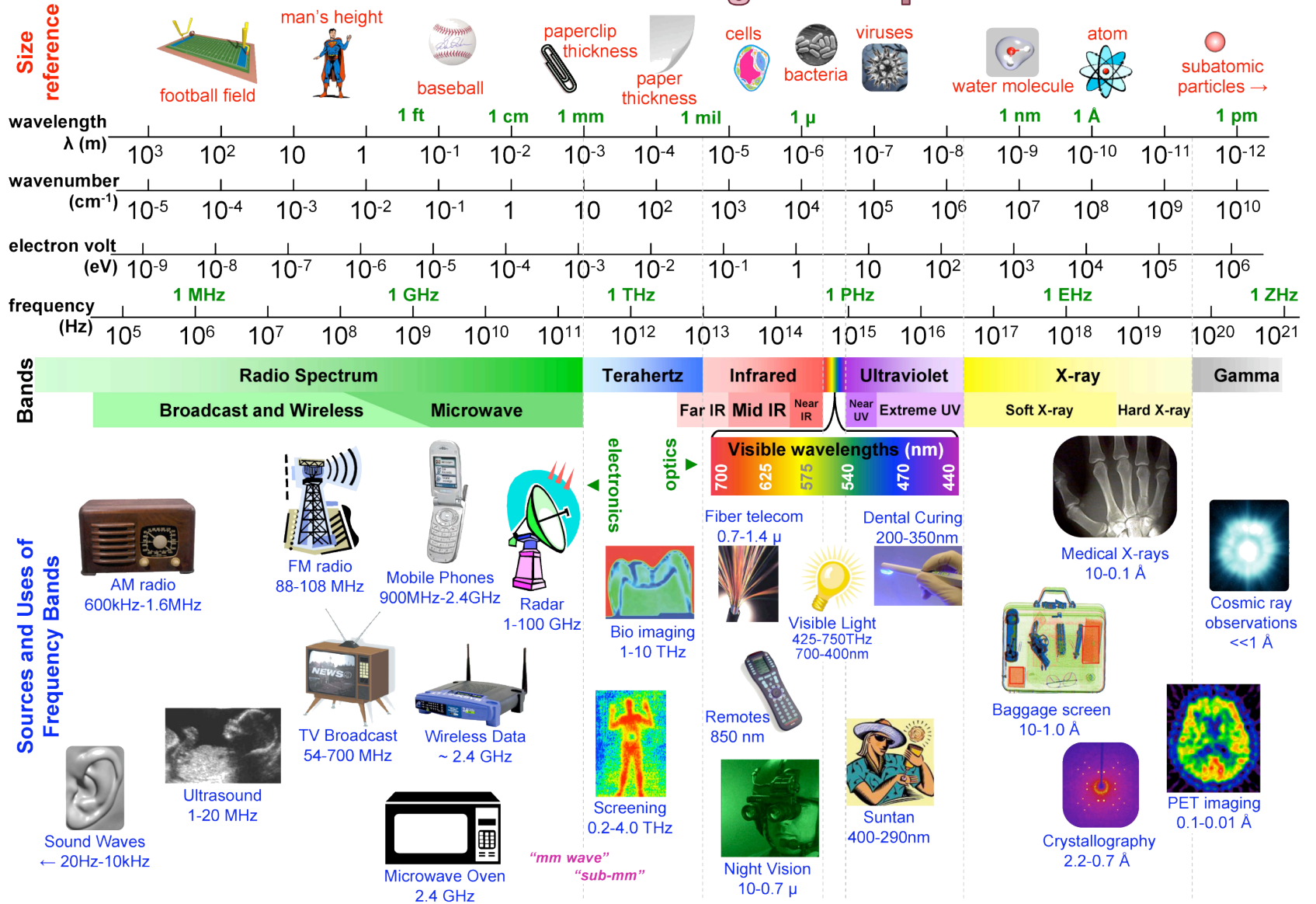


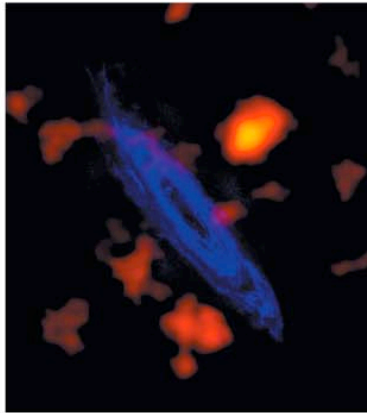
Chart of the Electromagnetic Spectrum



$$\lambda = 3 \times 10^8 / \text{freq} = 1 / (\text{wn} \times 100) = 1.24 \times 10^{-6} / \text{eV}$$

the electromagnetic spectrum

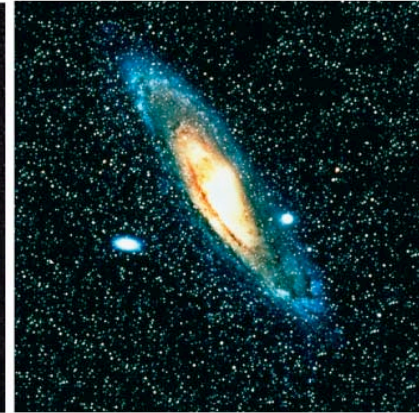
- we can only see the visible part of the spectrum, but the rest is out there too and can be detected with special instruments
- e.g. astrophysical objects emit radiation over a large region of the spectrum



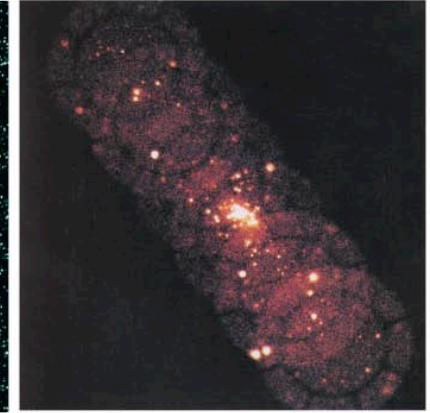
Radio This image combines a high-resolution radio image of the galaxy disk (blue) with a larger-scale image of the surrounding regions of space (red). Both images are sensitive to hydrogen gas. The clouds of hydrogen gas surrounding the galaxy are invisible in other spectral bands.



Infrared The wavelengths used for this image are particularly sensitive to the warm dust present in star-forming regions. Because these regions occur in galactic arms, the image shows the galaxy's arm structure especially clearly.



Visible In the visible we see mainly the light of stars, blocked in places by dark streamers of dust. Regions containing mostly old stars appear yellow white; star-forming regions containing young stars have a blue cast.



X-ray This x-ray image of the central part of the galaxy's disk shows many point sources of x rays, including a cluster near the galaxy's center. These points are mostly *x-ray binaries* containing a normal star orbiting a neutron star or black hole. The hot disk around the galaxy's central black hole also radiates x rays.



properties of electromagnetic waves?

- light having a certain frequency, wavelength and speed is traveling through empty space. If the frequency of the light were doubled, then
 - A. its wavelength would remain the same and its speed double
 - B. its wavelength would remain the same and its speed halve
 - C. its wavelength would be halved and its speed double
 - D. its wavelength halve and its speed remain the same

sinusoidal waves

- a very important type of wave is one whose time and space dependence is like that of the sine function
- a snapshot of one of these waves might look like
- mathematically we'd describe the wave:

$$E(x, t) = E_{\max} \sin \left(2\pi \left(ft - \frac{x}{\lambda} \right) \right)$$

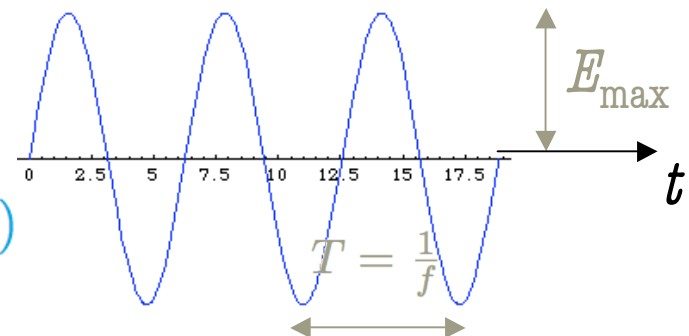
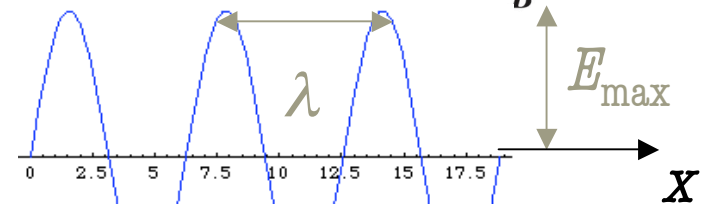
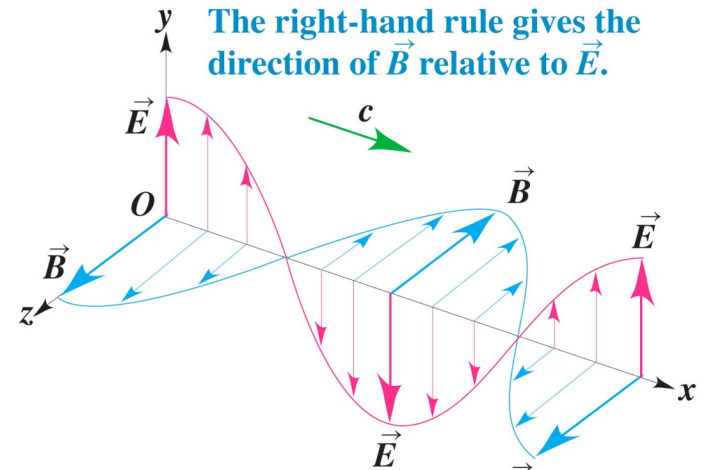
$$B(x, t) = B_{\max} \sin \left(2\pi \left(ft - \frac{x}{\lambda} \right) \right)$$

- e.g. a snapshot at time $t = 0$

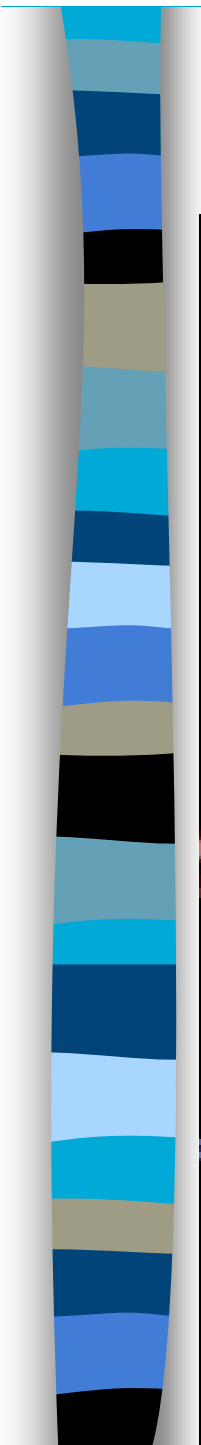
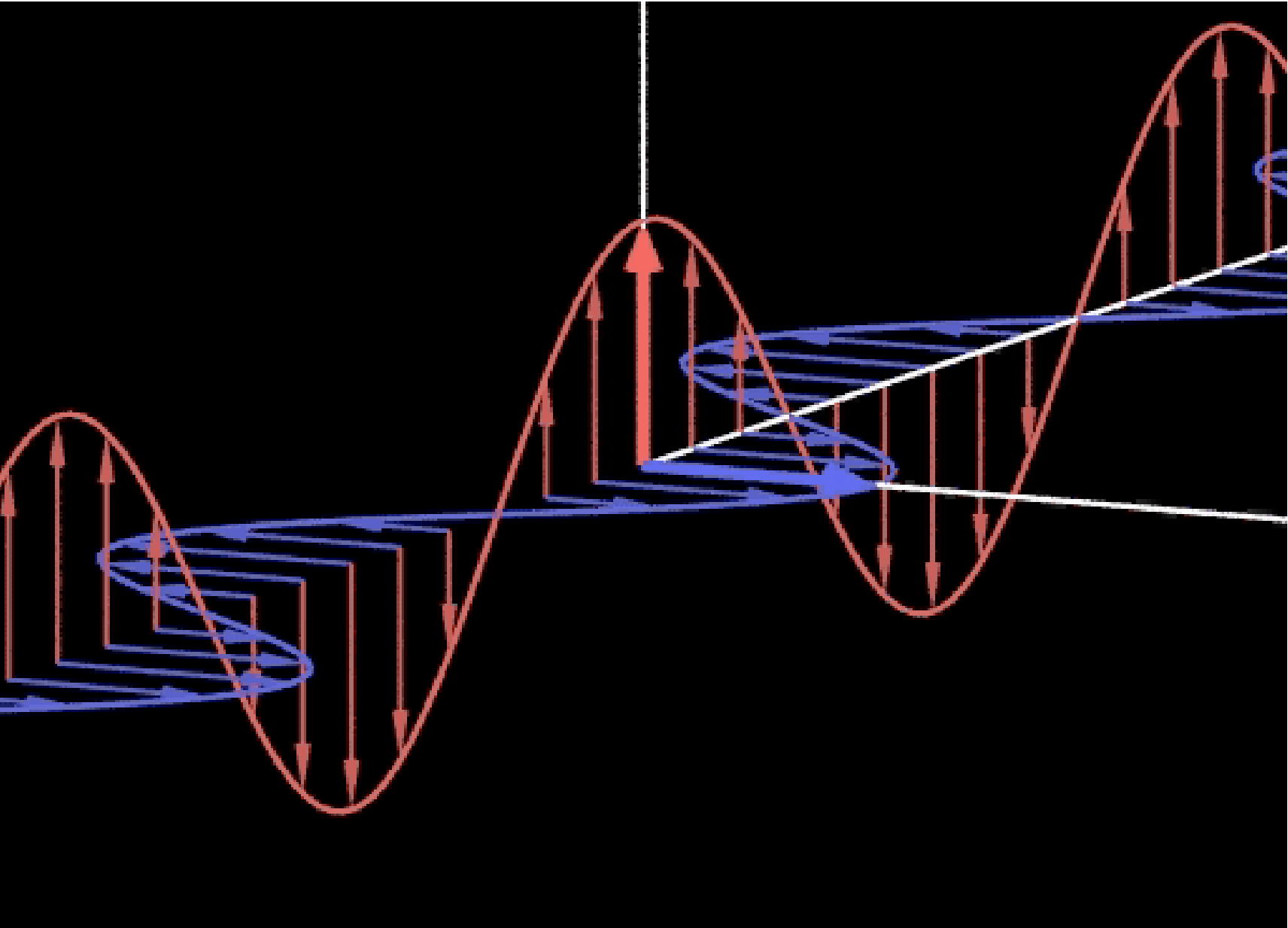
$$E(x, t) = E_{\max} \sin \left(2\pi \frac{x}{\lambda} \right)$$

- e.g. the time dependence at $x = 0$

$$E(x, t) = E_{\max} \sin (2\pi ft)$$



Electromagnetic Wave





energy in electromagnetic waves

- we've already learnt that setting up electric and magnetic fields requires input of energy (recall 'charging' a capacitor or an inductor coil)
- thus an em wave, being made up of electric and magnetic fields must have an energy content
- energy density for any electric and magnetic field

$$u = \frac{\epsilon_0}{2} E^2 + \frac{1}{2\mu_0} B^2$$

- but in a wave we said that

$$E = cB$$

- so $u = \epsilon_0 E^2$

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

- in other words in an em wave the electric and magnetic fields share the energy equally

energy **flow** in electromagnetic waves

- let's go back to our simple em wave
- $E=0, B=0$ to the right of the 'wave-front'

- in time Δt the wave-front advances through a distance $c\Delta t$

- consider an area of wave-front, A

- then the new volume now housing E,B-fields is $\Delta V = c\Delta t A$

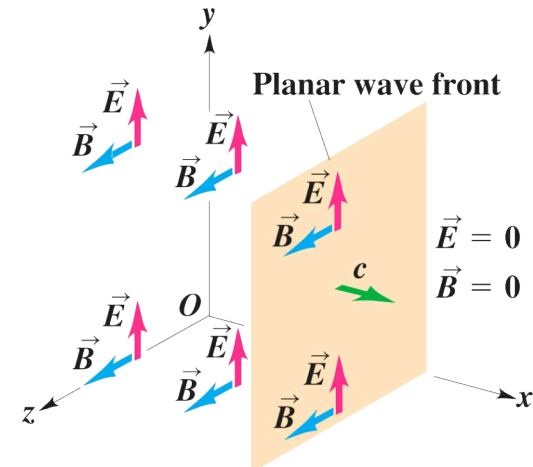
- and the energy housed is

$$\Delta U = u\Delta V = \epsilon_0 E^2 c\Delta t A$$

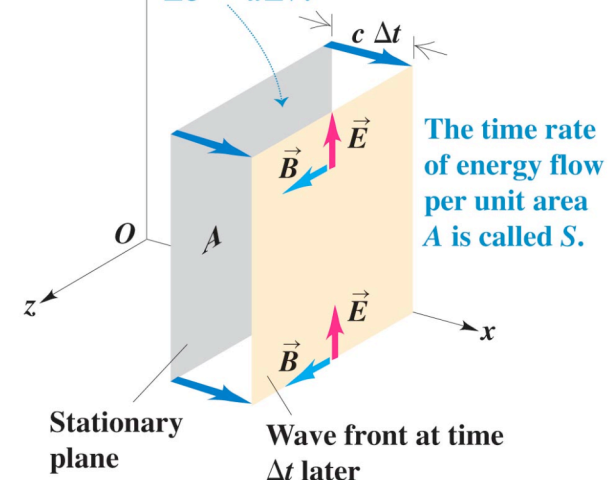
- energy flow per unit area per unit time

$$S = \frac{1}{A} \frac{\Delta U}{\Delta t} = \epsilon_0 c E^2 = cu$$

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



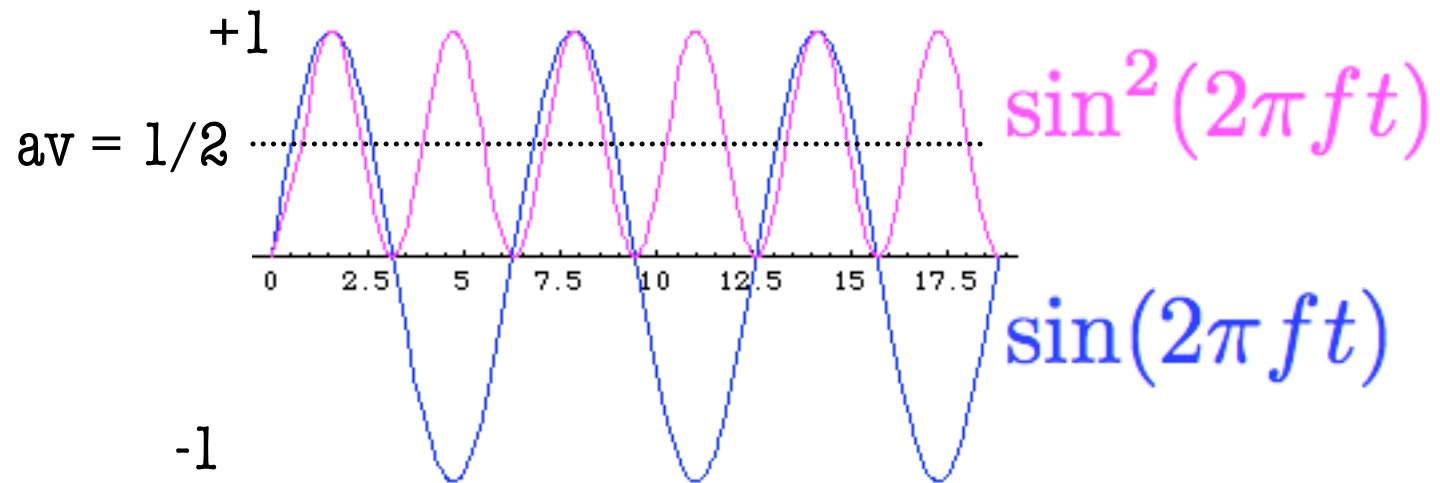
At time Δt , the volume between the plane and the wave front contains an amount of electromagnetic energy $\Delta U = u\Delta V$.



energy **flow** in electromagnetic waves

- what about in the case of a sinusoidal wave?
- here the intensity varies with time

- e.g. at $x=0$ $S = \epsilon_0 c E^2 = \epsilon_0 c E_{\max}^2 \sin^2(2\pi ft)$



- average over time $S_{av} = \frac{1}{2} \epsilon_0 c E_{\max}^2 = c u_{av}$
- average energy flow is often called the *intensity*



energy **flow** in electromagnetic waves

- if a sinusoidal electromagnetic wave with intensity 10 W/m^2 has an electric field of magnitude E at a given time and place, then a 20 W/m^2 wave of the same wavelength will have an electric field of magnitude

- A $4E$

- B $2\sqrt{2}E$

- C $2E$

- D $\sqrt{2}E$

$$S_{\text{av}} = \frac{1}{2} \epsilon_0 c E_{\text{max}}^2 = c u_{\text{av}}$$

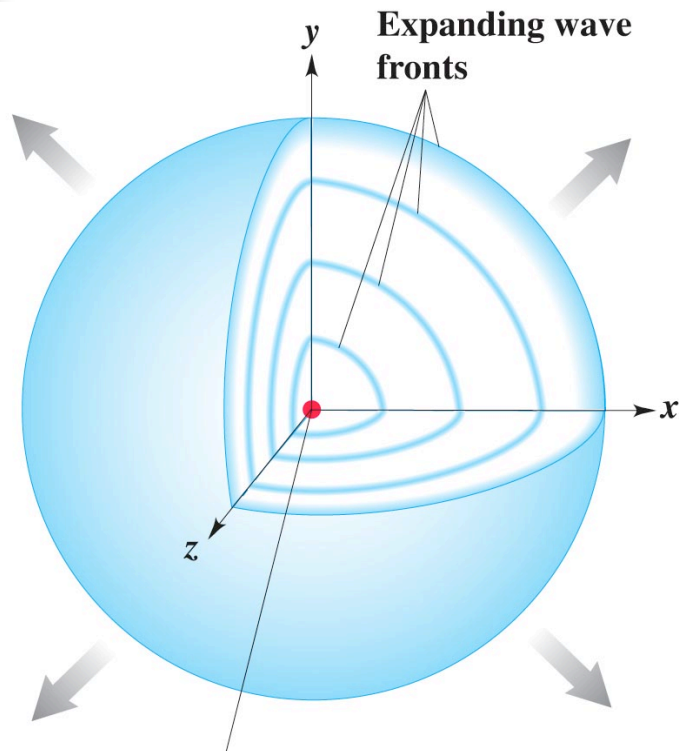


the nature of light

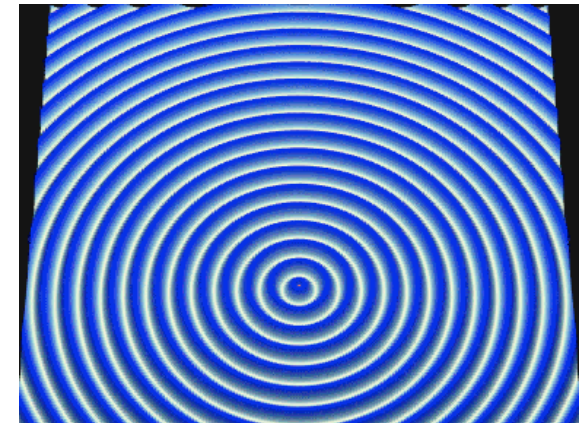
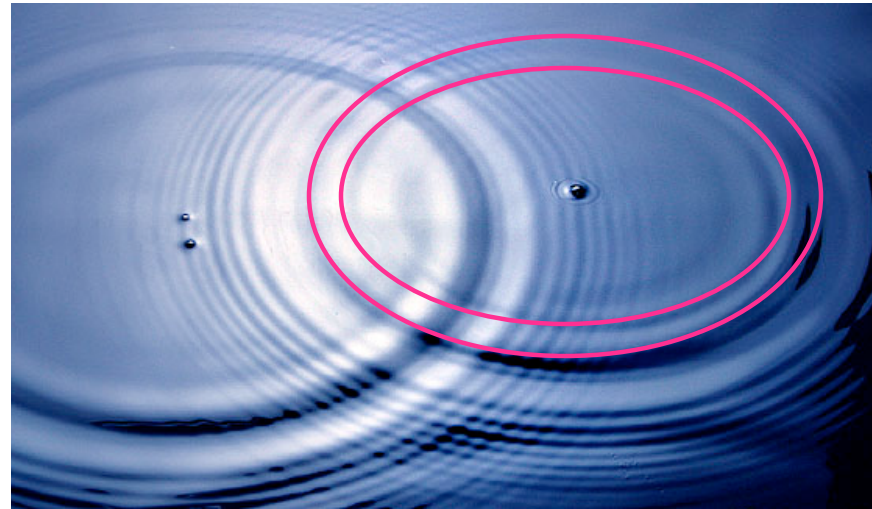
- for our purposes we will treat light as an electromagnetic wave
- later on we'll see that in some circumstances light behaves like a particle
- both of these views are actually true and we have a good theory that explains it, but it usually takes 5/6 years of math/physics training to be ready to take on this theory
- in virtually all 'everyday' experiences, light can be considered to be a wave
- lets see how far that gets us

wave-fronts

- a wave-front is a handy concept in understanding waves
- defined as the surface on which the phase of a wave is the same, i.e. where the wave is at the same bit of the vibration

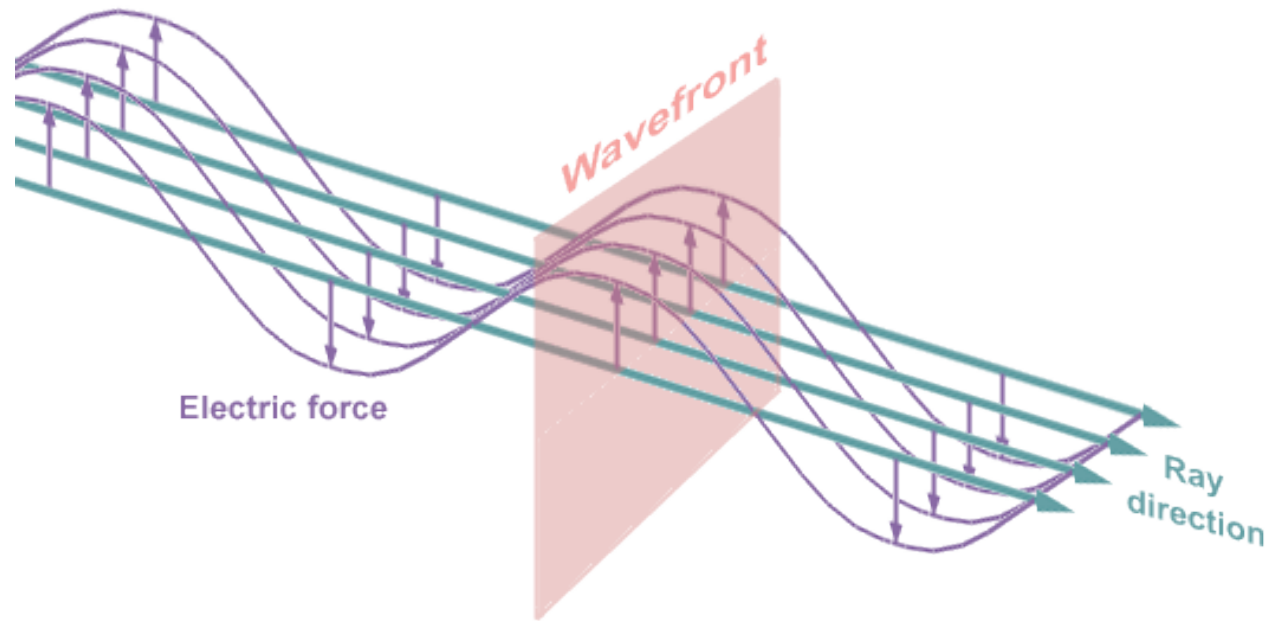


Point sound source producing spherical sound waves (alternating condensations and expansions of air)



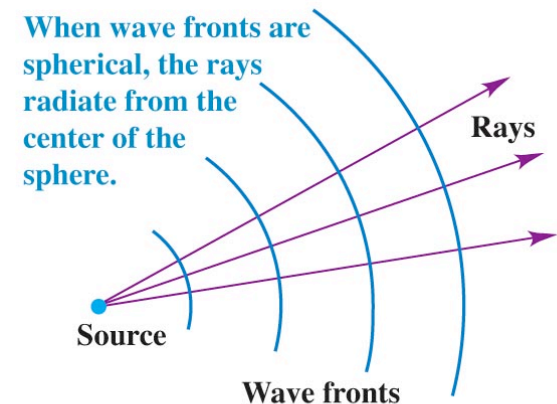
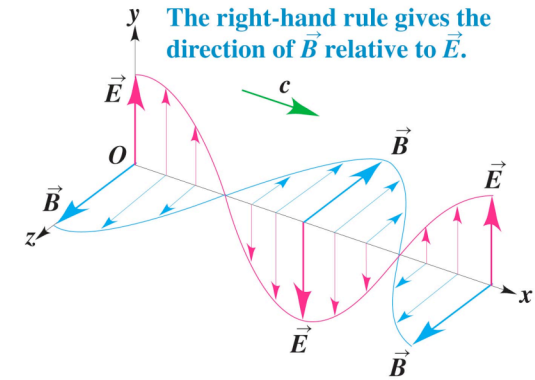
wave-fronts

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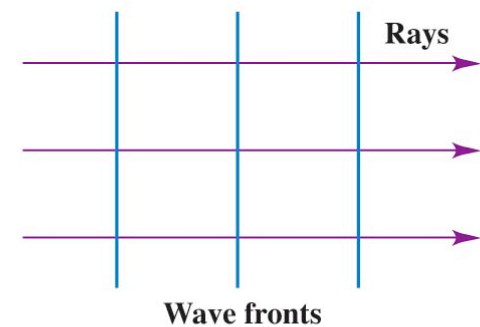
wave-fronts and rays

- for light the equivalent of the high-pressure areas for sound, or the raised water level for water waves, is the magnitude of the electric or magnetic field
- can also define *rays* which are imaginary lines at right angles to the wavefronts
- rays are very handy for describing *geometric optics*



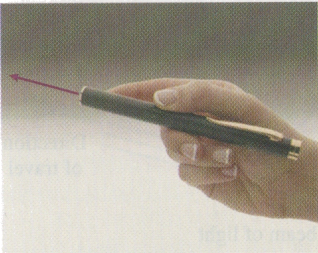
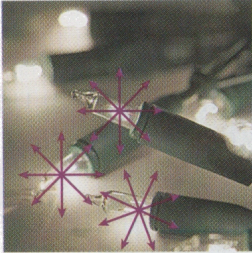
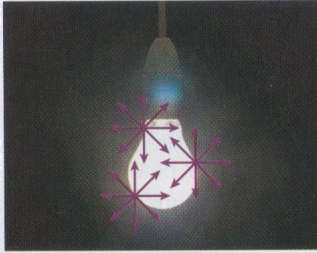
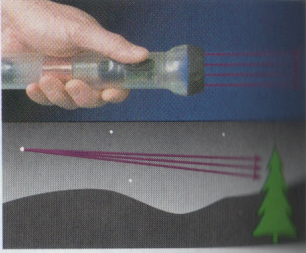
(a)

When wave fronts are planar, the rays are perpendicular to the wave fronts and parallel to each other.



describing light via rays

■ self-luminous object emit light rays

A ray source	A point source	An extended source	A parallel-ray source
			
Since a light ray is an idealization, there are no true ray sources. Still, the thin beam of a laser is often a good approximation of a single ray.	A point source is also an idealized source of light. It is infinitely small, and emits light rays in every direction. The tiny filaments of these bulbs approximate point sources.	This is the most common light source. Every point of an extended source acts as a point source. Light bulbs, flames, and the sun are extended sources.	Certain sources, such as flashlights and movie projectors, produce a bundle of parallel rays. Rays from a very distant object, such as a star, are very nearly parallel.

■ rays themselves are not visible as they travel through air



FIGURE 18.3 A laser beam traveling through air is invisible.

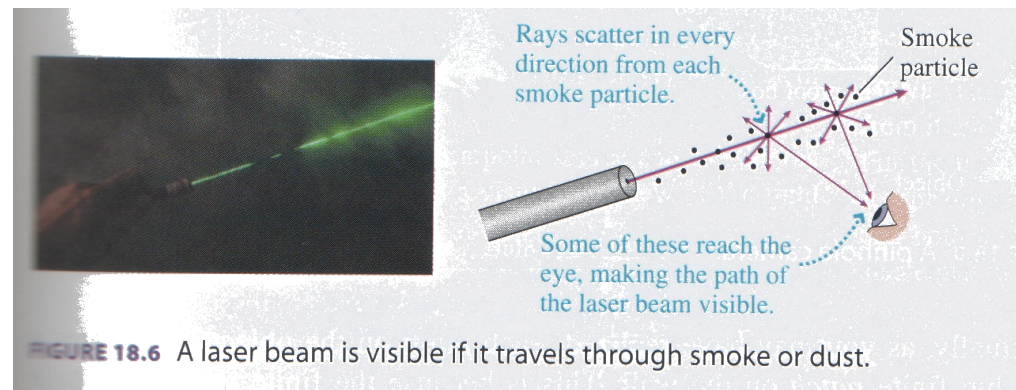
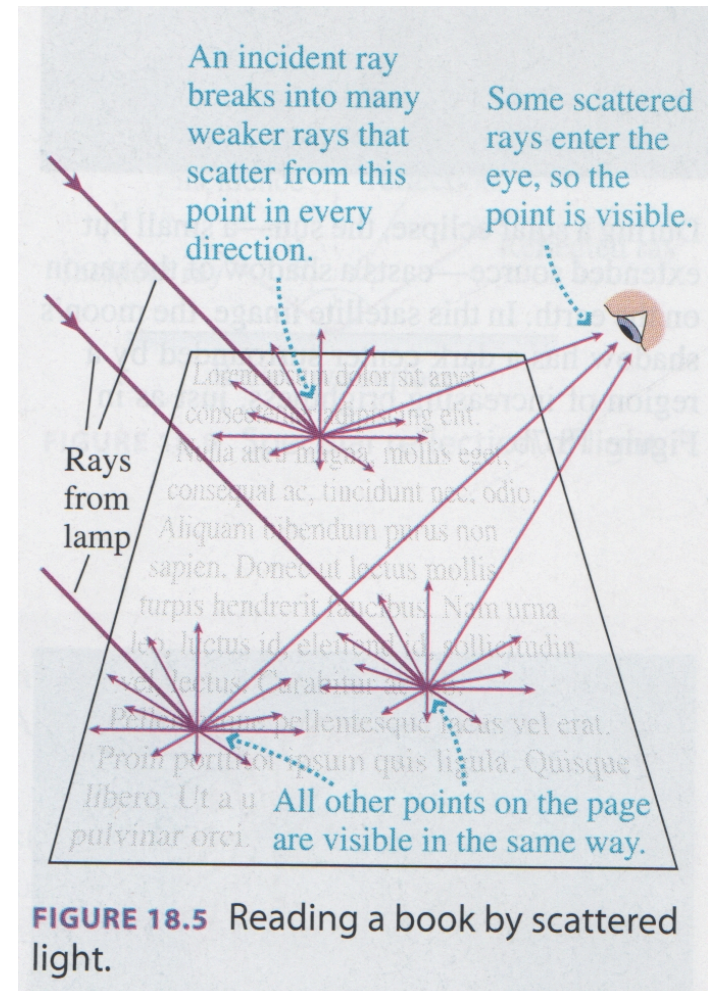


FIGURE 18.6 A laser beam is visible if it travels through smoke or dust.

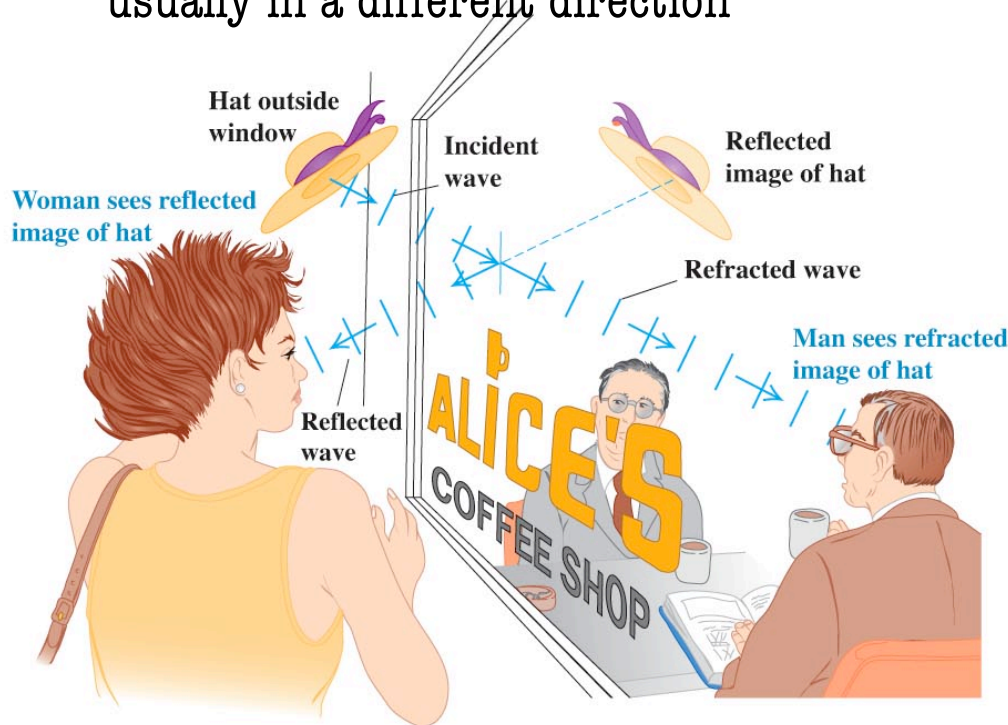
describing light via rays

- objects which are not self-luminous can be seen using light 'scattered' from their surfaces
- e.g. reading a page:
- 'scattering' occurs at 'rough' surfaces
- what about smooth surfaces?

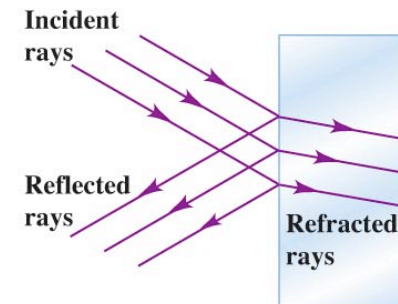


describing light via rays

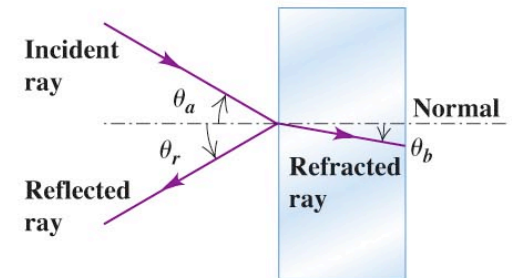
- when light moves from one medium to another (say from air to glass) two things can happen
 - some light can be *reflected*, continuing to propagate in the air, but in a new direction
 - some light can be *refracted*, propagating then through the glass, usually in a different direction



(a) Plane waves reflected and refracted from a window.



(b) The waves in the outside air and glass represented by rays.



(c) The representation simplified to show just one set of rays.



speed of light in a medium & refractive index

- in a material, light always travels somewhat **slower** than it does in vacuum
- basically this is due to interactions with the charges
- we can define a quantity, the index of refraction, that is the ratio of the speed of light in a vacuum to the speed in a material

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

$$n \geq 1$$

- this is the number that determines the optical properties of a material

big index of refraction means slower light



index of refraction

TABLE 23.1 Index of refraction for yellow sodium light ($\lambda_0 = 589 \text{ nm}$)

Substance	Index of refraction, n	Substance	Index of refraction, n
<i>Solids</i>		Medium flint	1.62
Ice (H_2O)	1.309	Dense flint	1.66
Fluorite (CaF_2)	1.434	Lanthanum flint	1.80
Polystyrene	1.49	<i>Liquids at 20°C</i>	
Rock salt (NaCl)	1.544	Methanol (CH_3OH)	1.329
Quartz (SiO_2)	1.544	Water (H_2O)	1.333
Zircon ($\text{ZrO}_2 \cdot \text{SiO}_2$)	1.923	Ethanol ($\text{C}_2\text{H}_5\text{OH}$)	1.36
Fabulite (SrTiO_3)	2.409	Carbon tetrachloride (CCl_4)	1.460
Diamond (C)	2.417	Turpentine	1.472
Rutile (TiO_2)	2.62	Glycerine	1.473
<i>Glasses (typical values)</i>		Benzene	1.501
Crown	1.52	Carbon disulfide (CS_2)	1.628
Light flint	1.58		



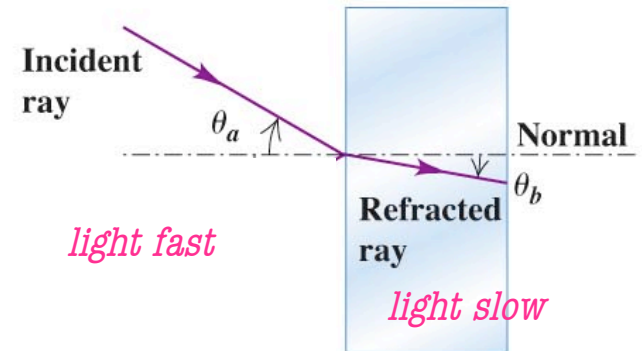
reading quiz

- a glass has a refractive index of 1.50. How fast does light travel in this glass?
 - *A. 4.5×10^8 m/s*
 - *B. 2.0×10^8 m/s*

- a large glass block has an air bubble in the middle. Can light in the air bubble undergo total internal reflection?
 - *A. yes, if the angle of incidence is large enough*
 - *B. no, because the refractive index of glass is larger than that of air*

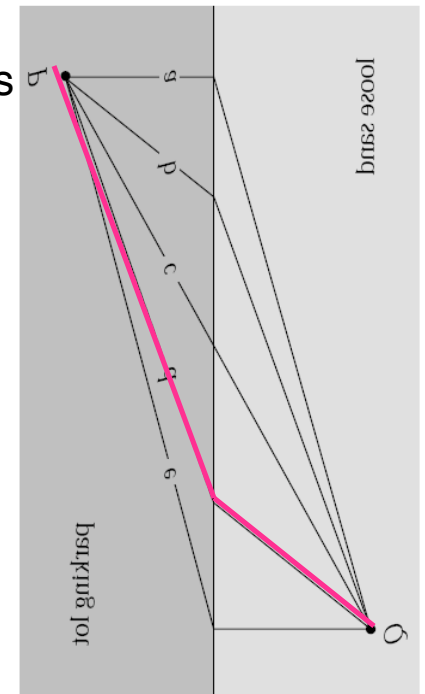
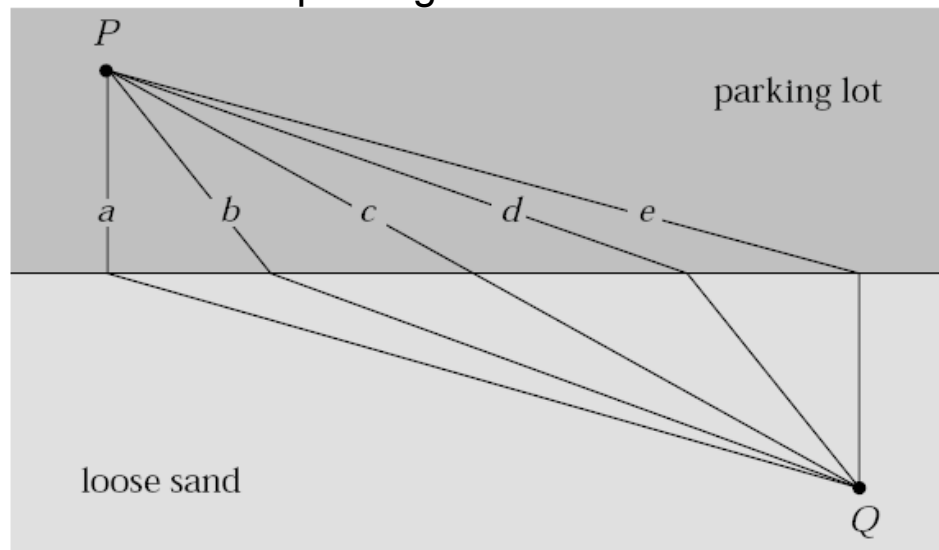
deflection of light rays & slowing of light

- light traveling slower in a material causes rays to bend at the interface
- why?
- consider this analogy:



A group of sprinters gather at point P on a parking lot bordering a beach. They must run across the parking lot to a point Q on the beach as quickly as possible. Which path from P to Q takes the least time? You should consider the relative speeds of the sprinters on the hard surface of the parking lot and on loose sand.

- A. a
- B. b
- C. c
- D. d



principles of geometric optics

- set of 'rules' for light rays which can be verified experimentally or derived starting from electromagnetism equations

- the incident, reflected and refracted rays are all in the same plane along with the normal to the surface (so we can draw on a page of paper)

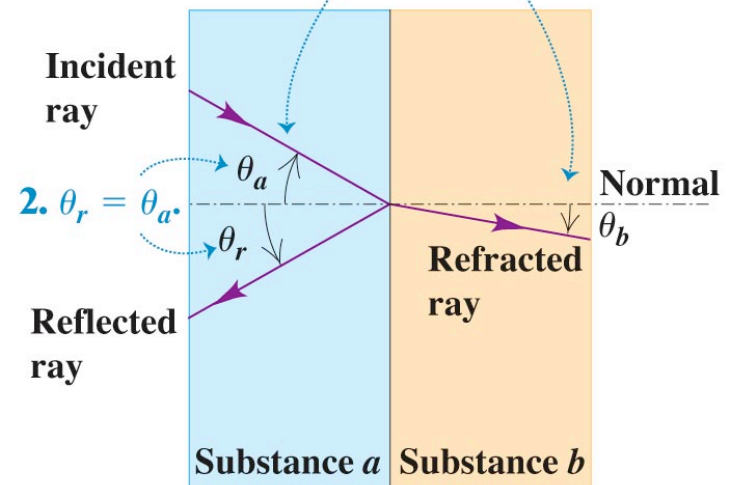
- **the angle of reflection is equal to the angle of incidence**

- **for a fixed frequency of light, Snell's law holds:**

$$n_a \sin \theta_a = n_b \sin \theta_b$$

1. The incident, reflected, and refracted rays and the normal to the surface all lie in the same plane.

Angles θ_a , θ_b , and θ_r are measured from the normal.



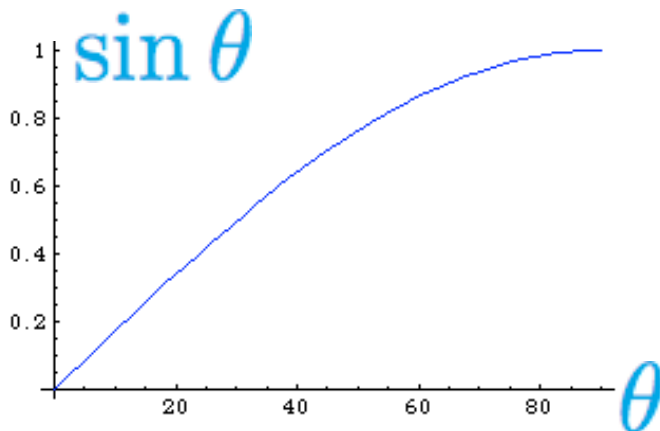
3. When a monochromatic light ray crosses the interface between two given substances a and b , the angles θ_a and θ_b are related to the indexes of refraction of a and b by

$$\frac{\sin \theta_a}{\sin \theta_b} = \frac{n_b}{n_a}$$

Snell's law of refraction

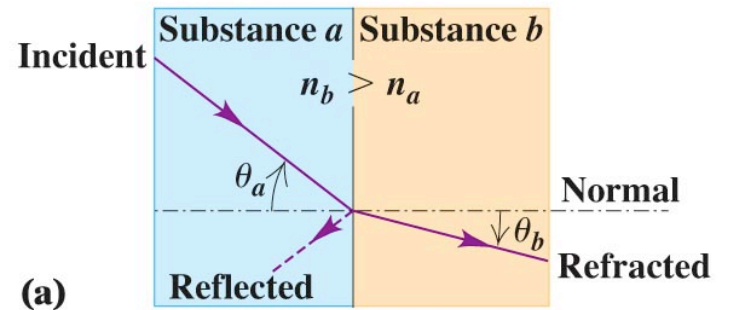
$$\frac{\sin \theta_a}{\sin \theta_b} = \frac{n_b}{n_a}$$

$$\sin \theta_b = \frac{n_a}{n_b} \sin \theta_a$$

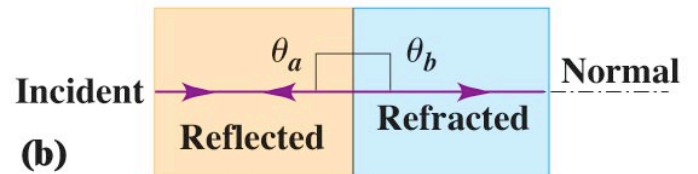


$$n_a \sin \theta_a = n_b \sin \theta_b$$

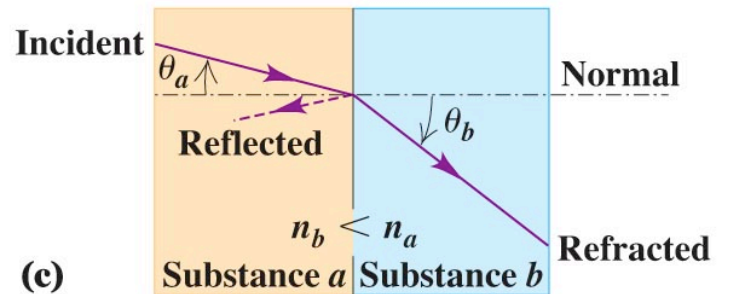
A ray entering a material of *larger* index of refraction bends *toward* the normal.



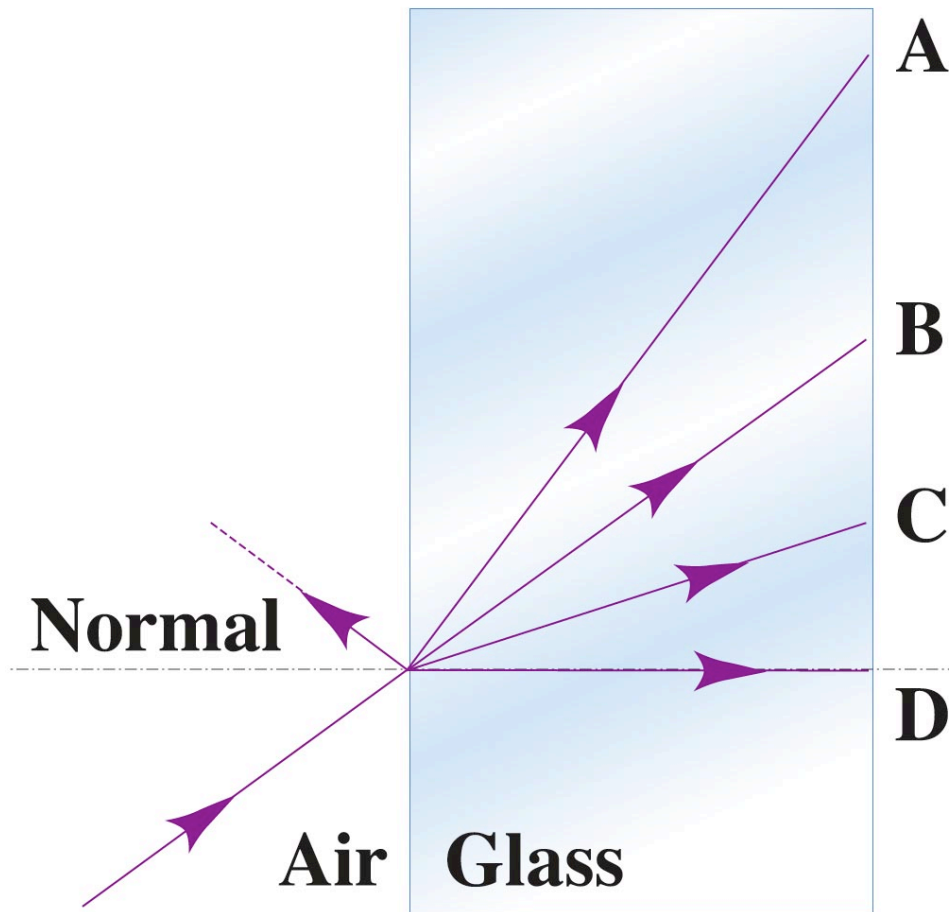
A ray oriented perpendicular to the surface does not bend, regardless of the materials.



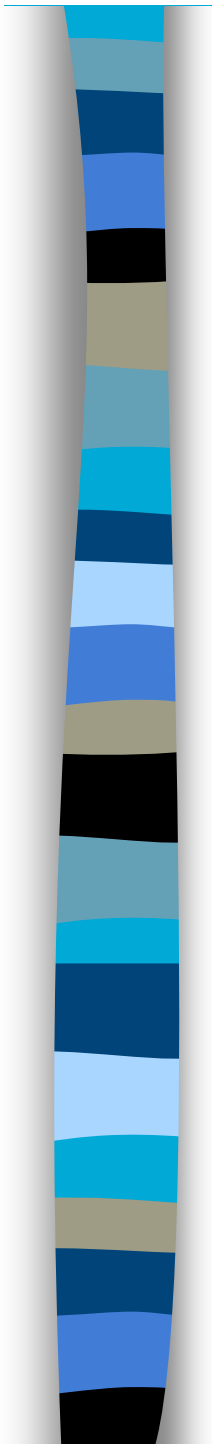
A ray entering a material of *smaller* index of refraction bends *away from* the normal.



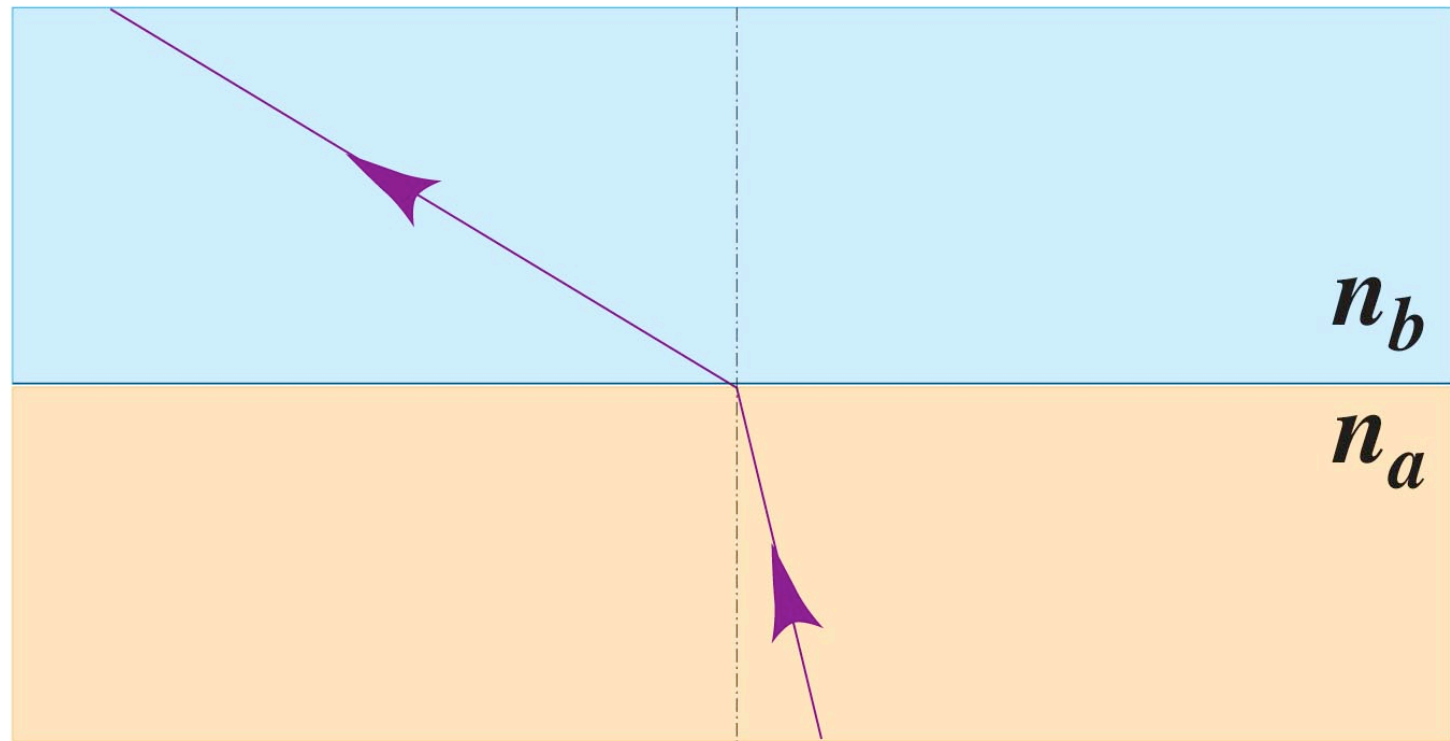
from air to glass



$$n_{\text{air}} < n_{\text{glass}}$$



refraction



(a) $n_a \geq n_b$

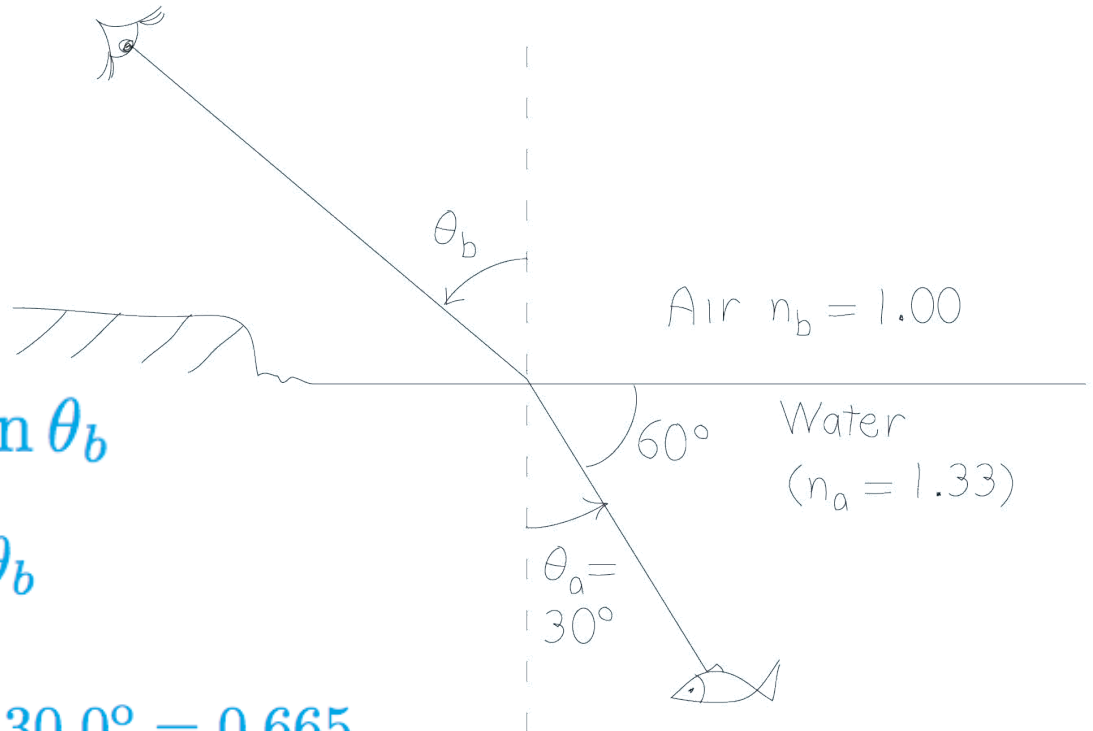
(c) $n_a < n_b$

(b) $n_a > n_b$

(d) $n_a \leq n_b$

fishpond

- you kneel over a fishpond and see a fish via sunlight which reflects off the fish and refracts at the water-air interface. If the light from the fish to your eye strikes the water-air interface at 60.0° to the interface, what is the angle of refraction of the ray in the air?



$$n_a \sin \theta_a = n_b \sin \theta_b$$

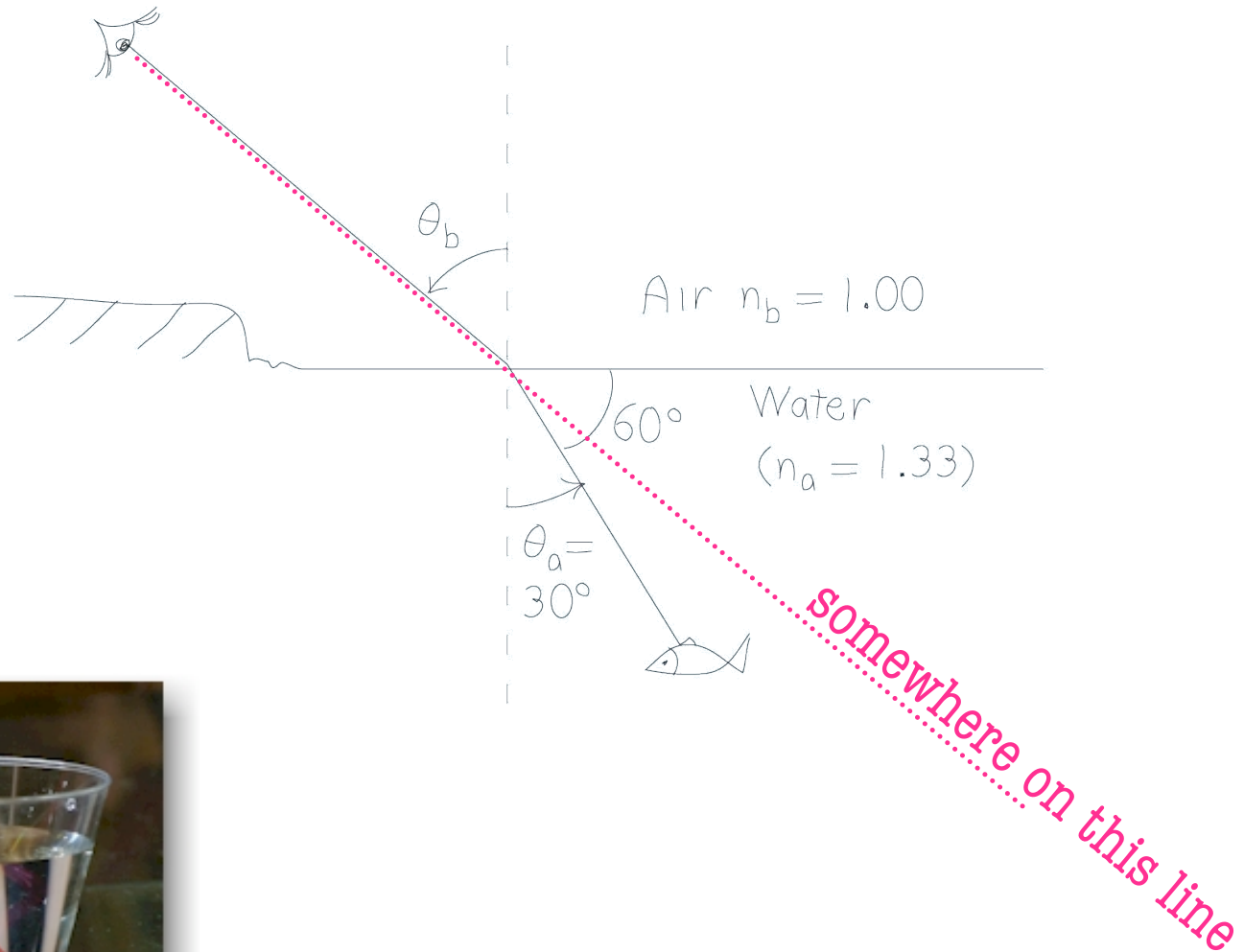
$$\sin \theta_a = \frac{n_b}{n_a} \sin \theta_b$$

$$\sin \theta_a = \frac{1.33}{1.00} \sin 30.0^\circ = 0.665$$

$$\theta_a = \sin^{-1} 0.665 = 41.7^\circ$$

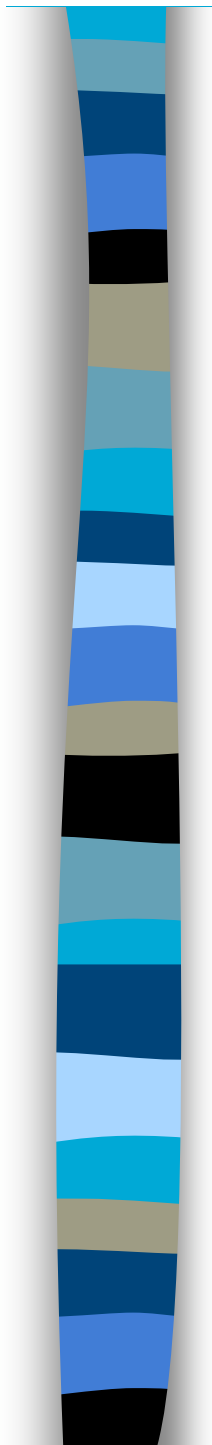
fishpond

- where does it appear to you that the fish is located?

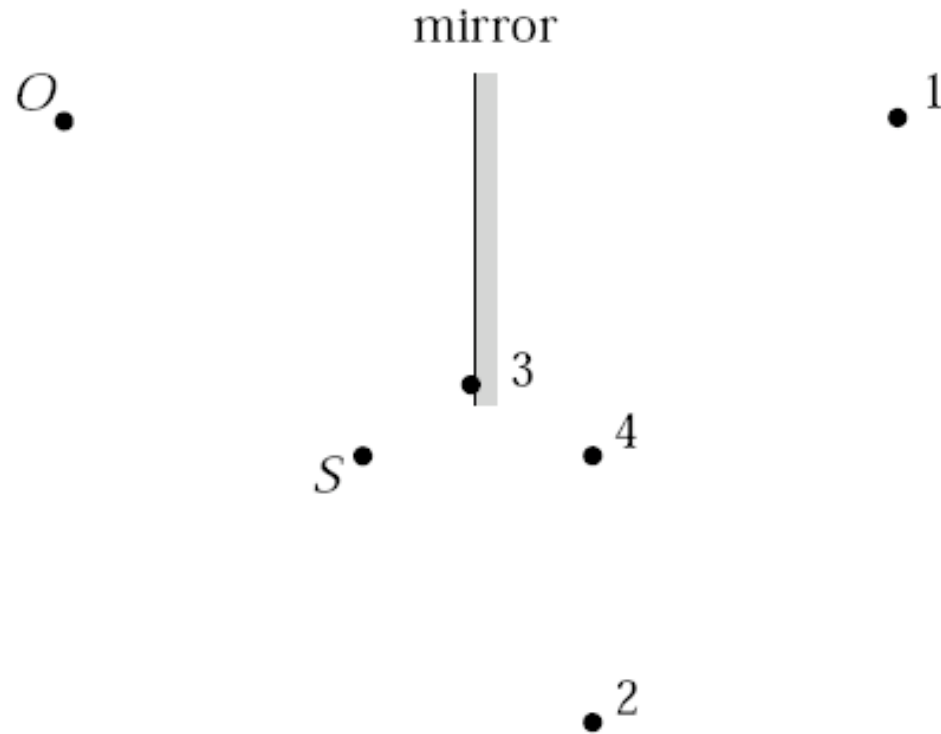


refraction is the origin of this classic optical illusion

more on this next time



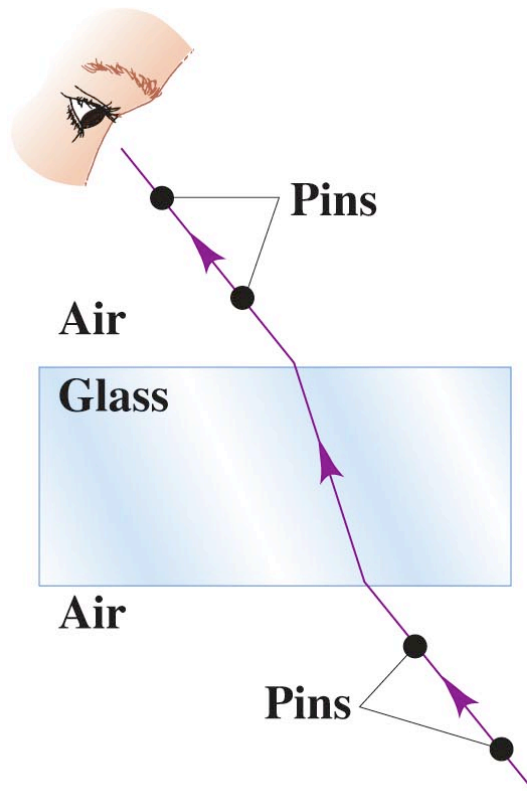
An observer O , facing a mirror, observes a light source S . Where does O perceive the mirror image of S to be located?



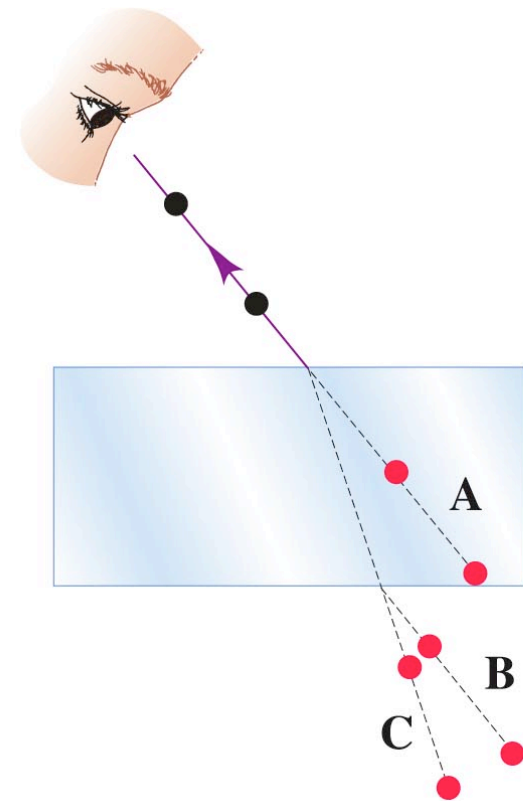
- A. 1
- B. 2
- C. 3
- D. 4

through a glass

- what is the *apparent* position of the pins?



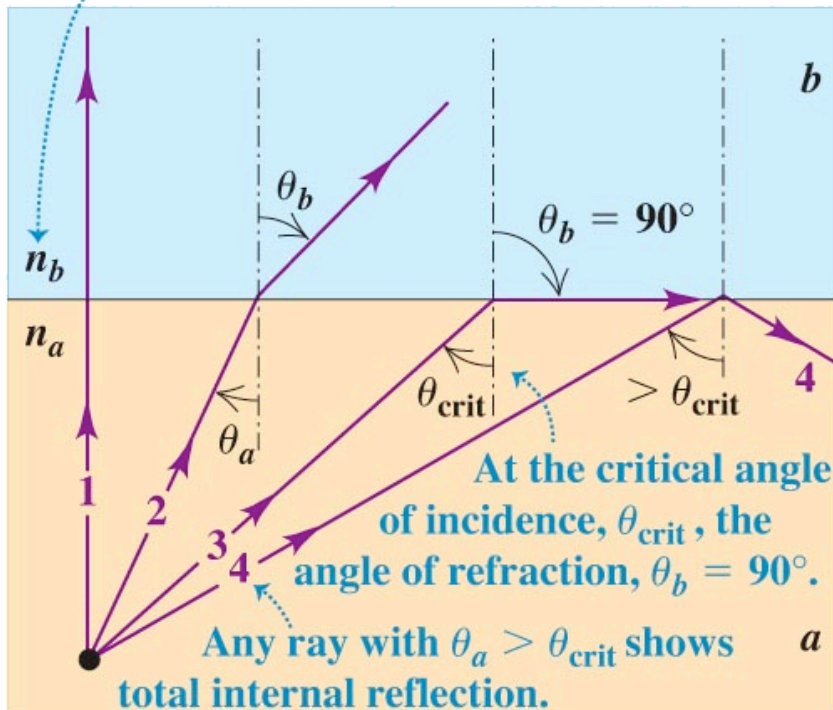
(a) Actual position of pins



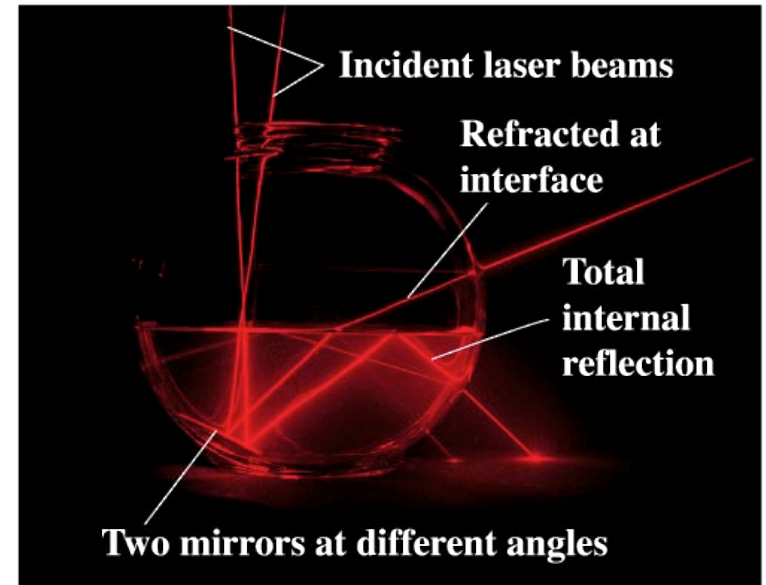
(b) Which choice represents the apparent position of the pins?

total internal reflection

Total internal reflection occurs only if $n_b < n_a$.



(a) Total internal reflection

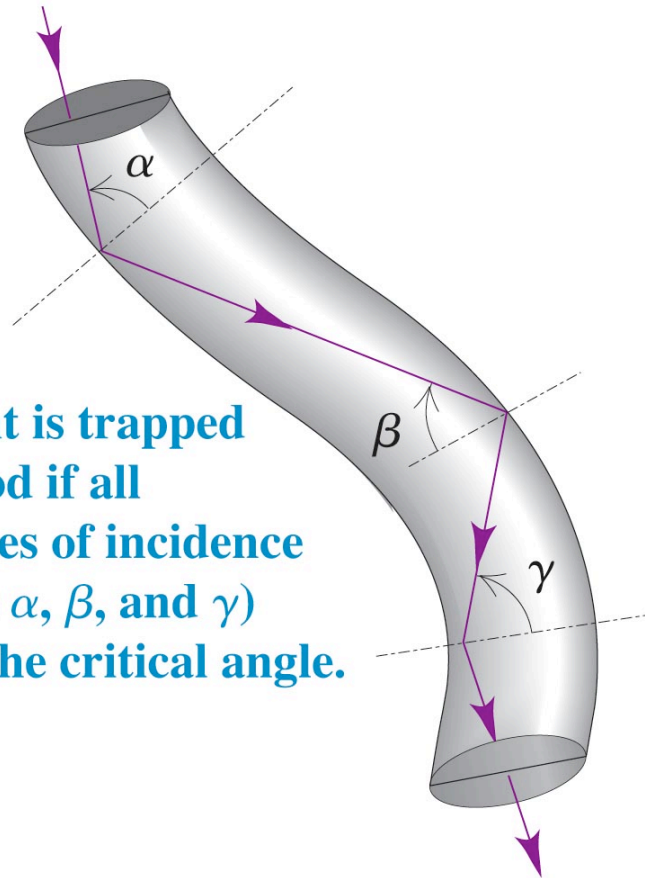


(b) Total internal reflection demonstrated with a laser, mirrors, and water in a fishbowl

$$\theta_b = 90^\circ$$

$$\sin \theta_{\text{crit}} = \frac{n_b}{n_a}$$

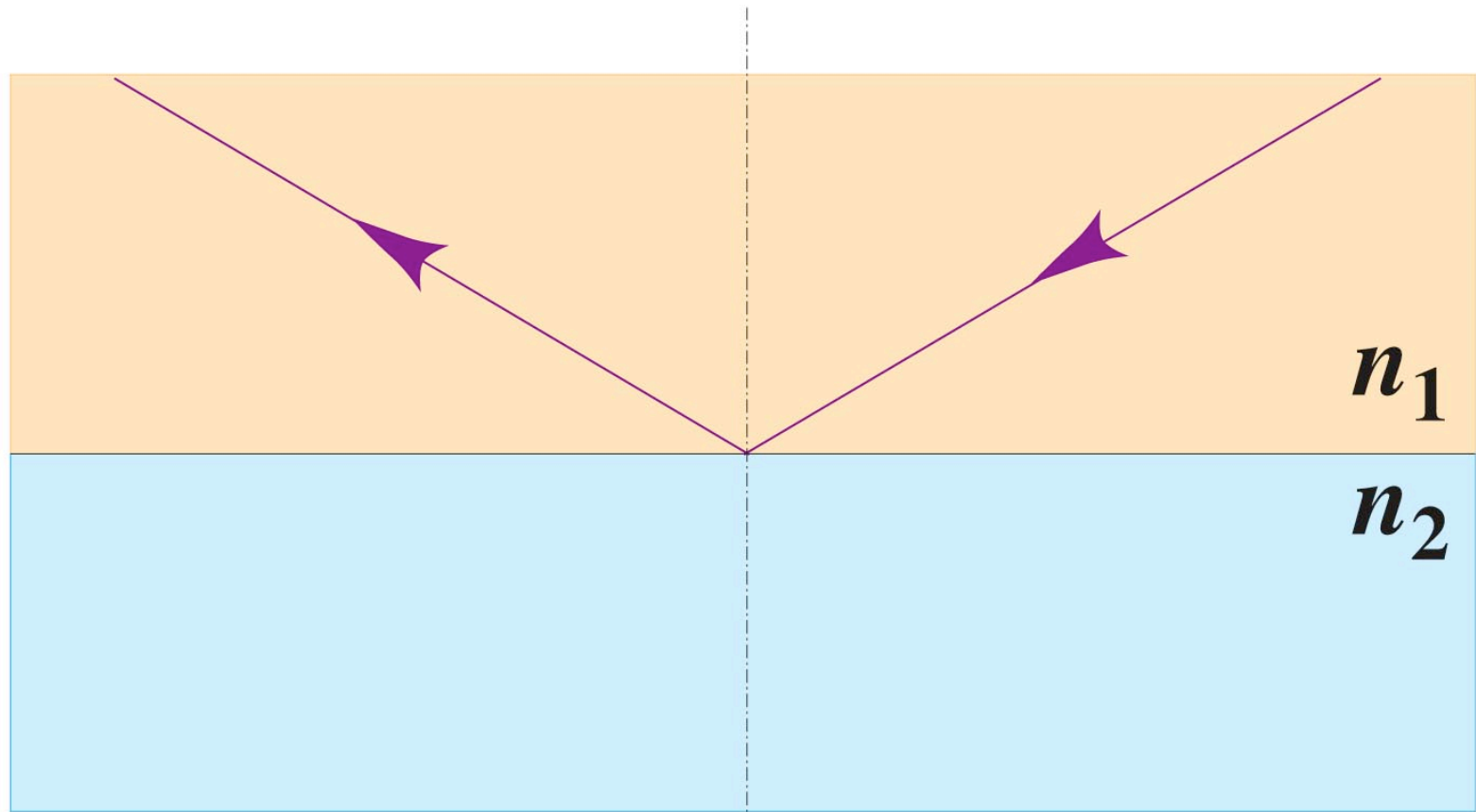
total internal reflection & fiber optic cables



The light is trapped in the rod if all the angles of incidence (such as α , β , and γ) exceed the critical angle.



two transparent materials:



(a) $n_1 > n_2$

(b) $n_1 \geq n_2$

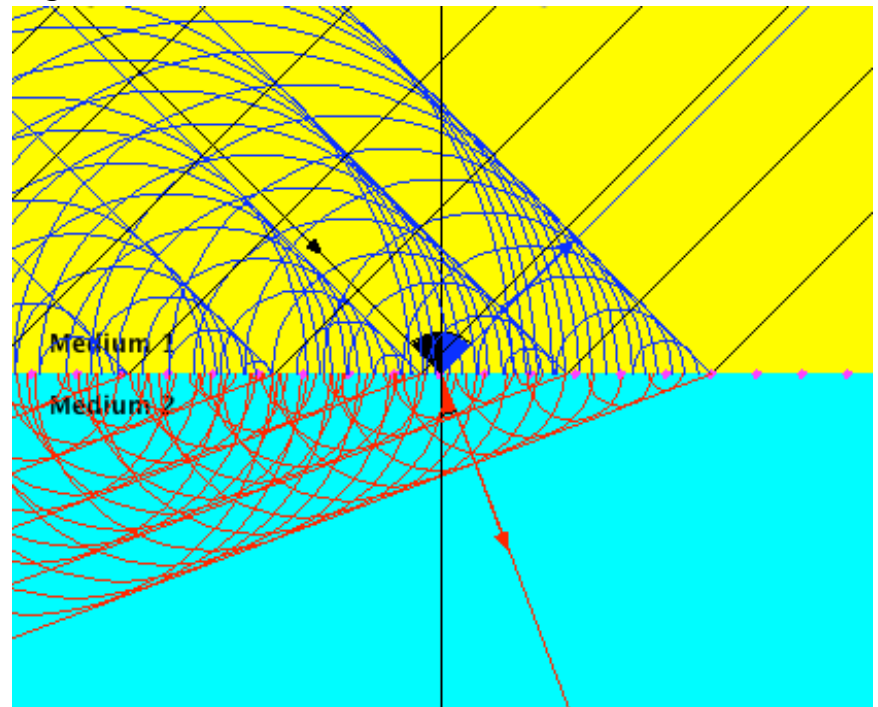
(c) $n_1 \leq n_2$

(d) $n_1 < n_2$

wavelength, frequency?

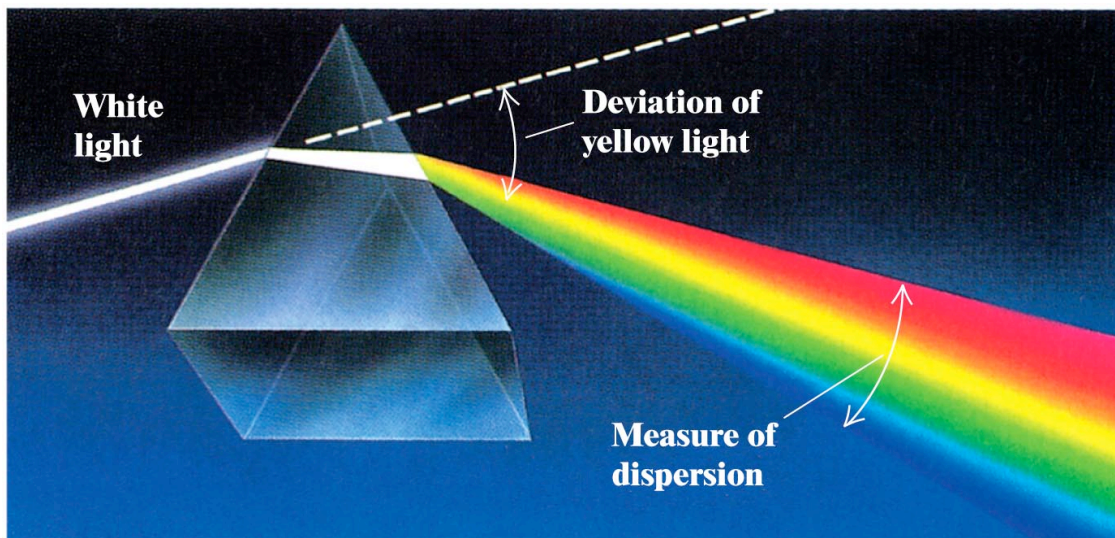
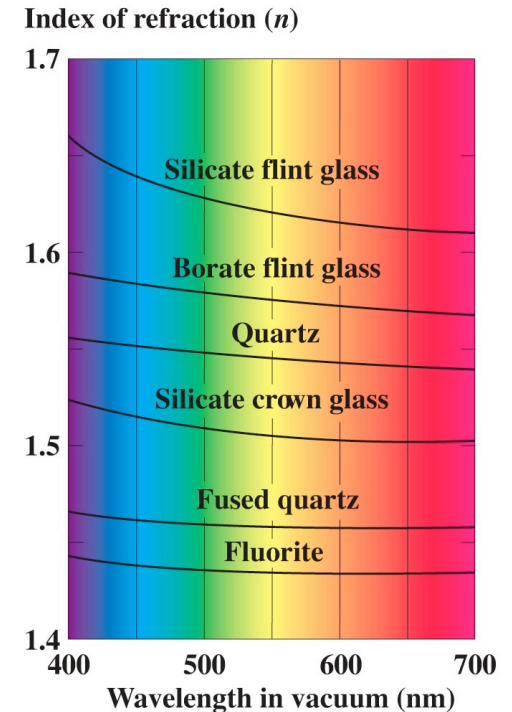
- in vacuum we said that $c = f\lambda$
- in a material, this still holds, but now the speed has changed
 - so either the frequency or the wavelength must change
- it is the wavelength that changes - the frequency, which is the number of wavefronts per unit time is unchanged

$$\lambda = \frac{\lambda_0}{n}$$



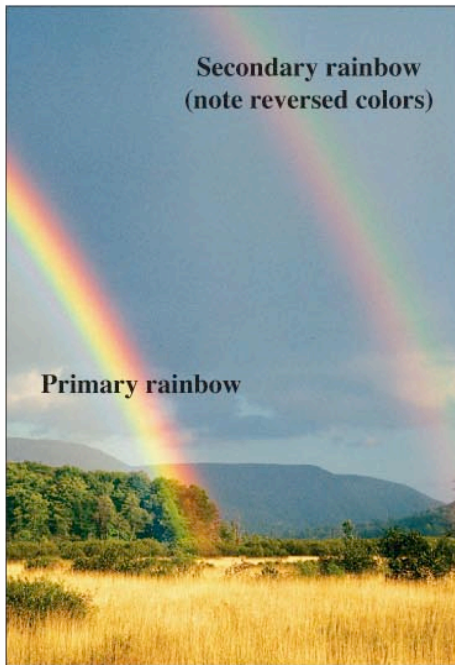
dispersion

- the refractive index of a material actually depends somewhat on the frequency of the light
- so different colors of light are 'bent' by different amount when they pass from air into a material
- since white light is a superposition of waves covering the whole visible spectrum, we see *dispersion* of white light into a spectrum

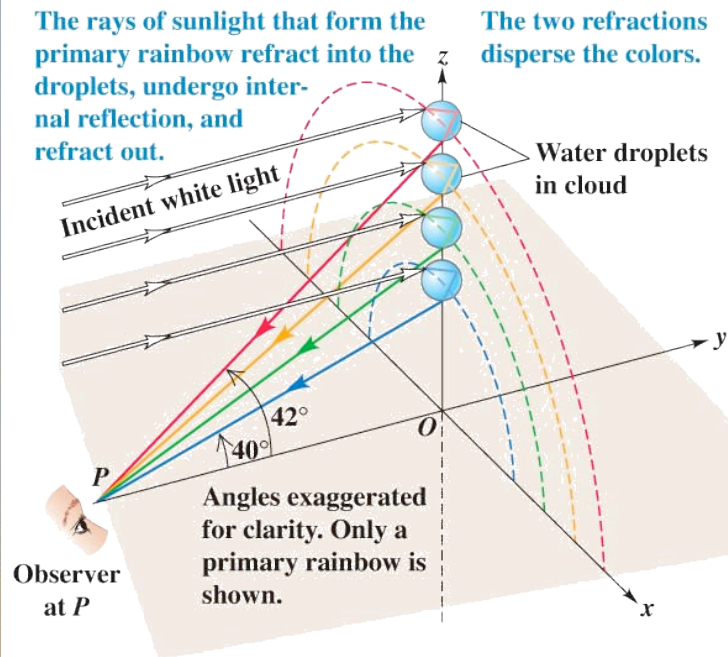


rainbows

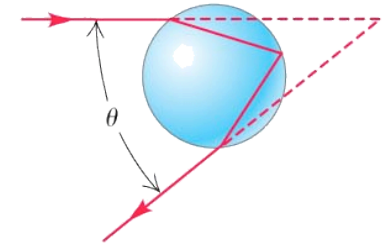
- when the material is water droplets in clouds and the light is from the sun we get rainbows



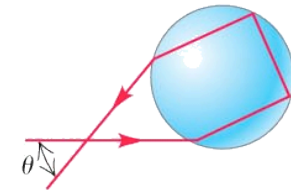
(a) A double rainbow.



(b) How refraction and reflection in cloud droplets forms a rainbow. The x - y plane is horizontal, the z axis vertical.



(c) An incoming ray undergoes two refractions and one internal reflection. The angle θ is greater for red light than for violet.



(d) A secondary rainbow is formed by rays that undergo two refractions and two internal reflections; the angle θ is greater for violet light than for red.