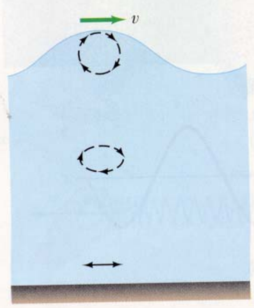
FIGURE 11–27 A water wave is an example of a *surface wave*, which is a combination of transverse and longitudinal wave motions.



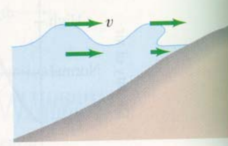


FIGURE 11–28 How a wave breaks. The green arrows represent the local velocity of water molecules.

ENERGY TRANSPORTED BY WAVES

Waves transport energy [not matter]
Waves travel through a medium [which IS matter]

- Vibratory energy is transferred from particle to particle $E = \frac{1}{2}kA^2$, thus $E \propto A^2$
- **Intensity**, I is equal to power (E/t) transported across unit area ⊥ to the direction of E flow

$$I = \frac{Power}{area} = \frac{E/t}{area} \therefore I \propto A^2$$

Three dimensional waves include sound in open air, seismic waves & light waves

- **spherical waves**--if the medium is isotropic [same throughout]

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

If the power output is constant, then ***intensity decreases as inverse square of the distance*** from the source:

$$I \propto \frac{1}{r^2}$$

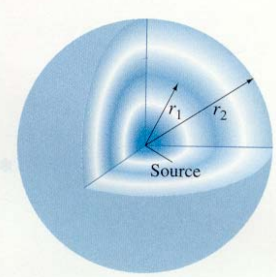


FIGURE 11–29 Wave traveling outward from source has spherical shape. Two different crests (or compressions) are shown, of radius r_1 and r_2.

Consider points r_1 and r_2 in figure 11.29 relative to the source:

$$I_1 = \frac{P}{4\pi r_1^2} \quad as\ well\ as \quad I_2 = \frac{P}{4\pi r_2^2}$$

So, when the distance from the source doubles, the intensity I is decreased by a factor of ¼.

Amplitude also decreases with distance since $I \propto A^2$ and A must decrease as $1/r$, so, as you double the distance the amplitude is decreased by a factor of ½. AND these relationships may prove handy:

$$\frac{I_2}{I_1} = \frac{r_1^2}{r_2^2} \quad and \quad \frac{A_2}{A_1} = \frac{r_1}{r_2}$$

Example 12

If the intensity of an earthquake P wave 100 km from the source is 1.0×10^6 W/m^2, what is the intensity 400 km from the source?

VERY different for a 1-D wave like a transverse wave on a string or a longitudinal wave traveling down a thin uniform metal rod. The area remains constant therefore, the amplitude remains constant and *A* & *I* DO NOT decrease with distance!

REFLECTION AND INTERFERENCE OF WAVES

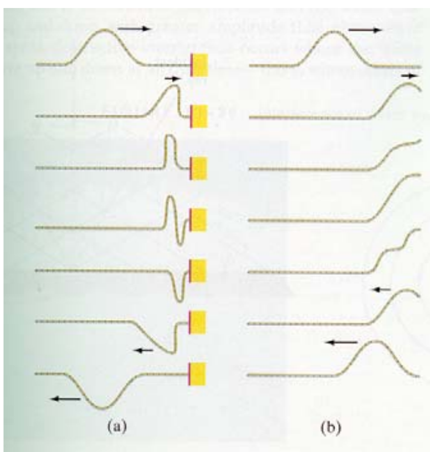


FIGURE 11–31 Reflection of a wave pulse on a cord when the end of the cord is (a) fixed and (b) free.

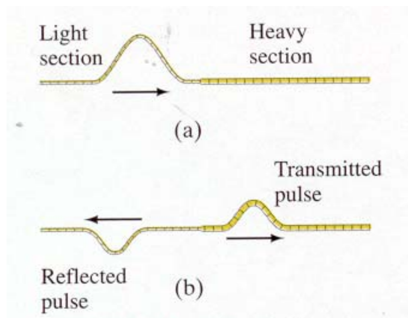
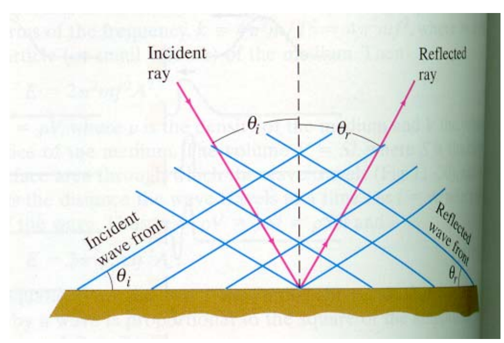


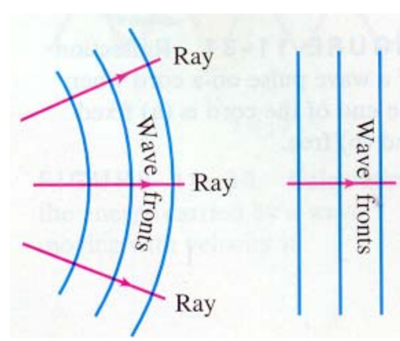
FIGURE 11–32 When a wave pulse traveling to the right (a) reaches a discontinuity, then (b) part is reflected and part is transmitted.

- **Reflection**--a wave strikes an obstacle and returns. When sound waves reflect, we hear an echo.

Some *E* is absorbed by wall and converted to thermal *E* and part continues to propagate through the material of the wall.



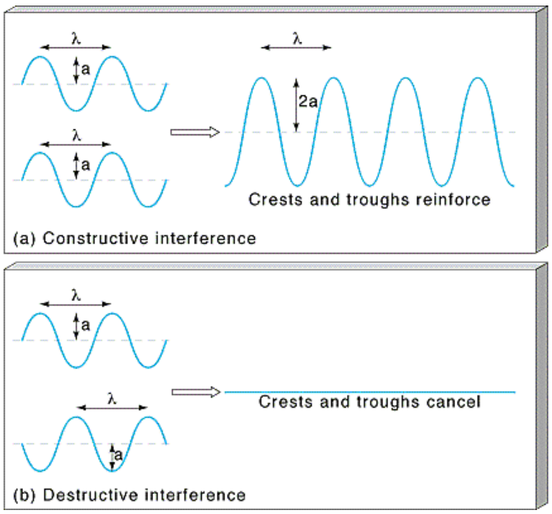
- **Wave front**--2-D or 3-D waves; whole width of a wave crest.
  Much like what you see as waves approach the beach.

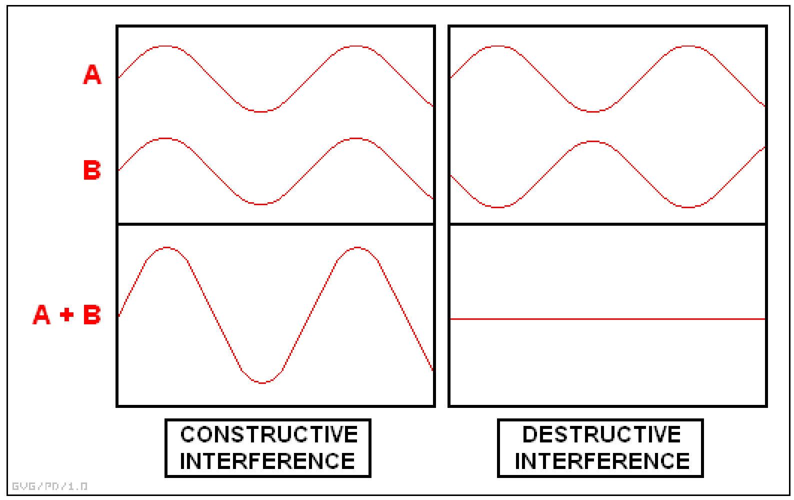


- **Plane waves**--Nearly straight wave fronts far from the source.

Law of Reflection: The angle of incidence θ_i= the angle of reflection θ_r

- **<u>Interference</u>**--happens when 2 waves pass through the same region of space at the same time
- **<u>Principle of superposition</u>**--the resultant displacement is the algebraic sum of their separate displacements. Crests are (+) and troughs are (−).
- Constructive vs. Destructive interference: a couple of different views.

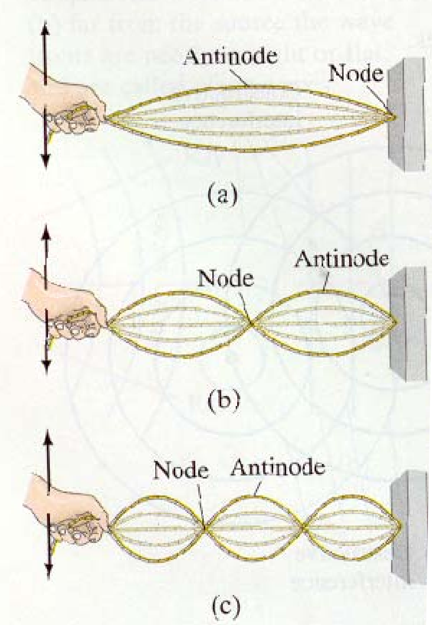




STANDING WAVES and RESONANCE

Standing waves are called that because they appear stationary. Envision a rope anchored at one end

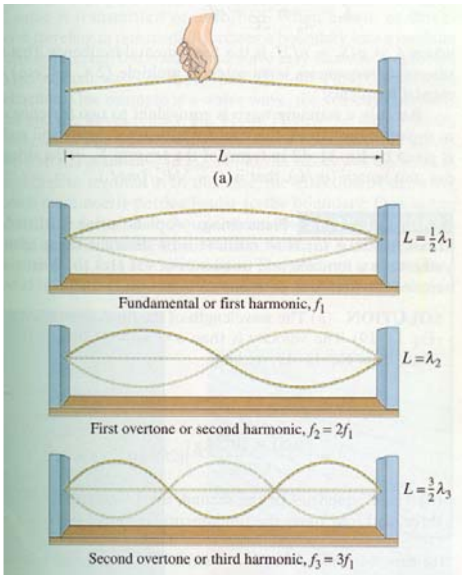
FIGURE 11-38 Standing waves corresponding to three resonant frequencies.

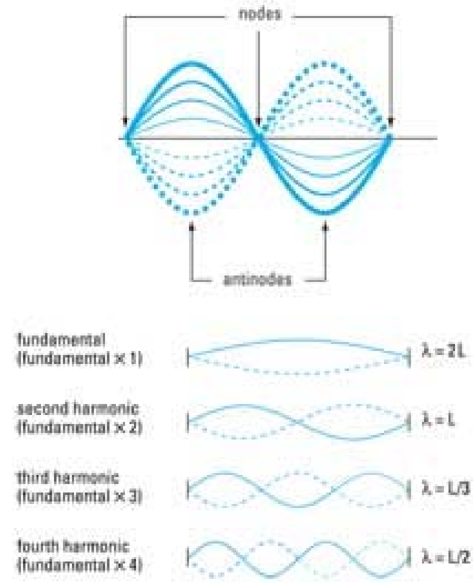


- **<u>nodes</u>**--points of destructive interference; $A = 0$
- **<u>antinodes</u>**--points of constructive interference; max A
- When a cord is fixed at one end, nodes and antinodes remain fixed for a given f. Standing waves can occur at more than one frequency
- Cords have a large number of resonant f, all whole number multiples of the lowest f.

What if cord is anchored at BOTH ends?

Pluck the string an a jumble of waves are set up interfering with each other. Most die out unless....you generate one of the resonant frequencies.





There are nodes at both ends, the fixed positions.

- **<u>Fundamental *f*</u>**--one antinode (loop or "hump"); changes with the length of the cord; L = ½ λ; first harmonic frequency
- **<u>overtones</u>**--other natural f that are integral multiples of the fundamental; also called harmonics
  - 1st overtone = 2nd harmonic $L = \lambda_2$
  - 2nd overtone = 3rd harmonic $L = 3/2\ \lambda_3$
  - 3rd overtone = 4th harmonic $L = 2\ \lambda_4$

$L = \frac{n\lambda_n}{2}$ where *n* labels the number of the harmonic, next solve for λ_n

$\lambda_n = \frac{2L}{n}$ *as well as* $f = \frac{v}{n}$ and, solve for each vibration $f_n = \frac{v}{\lambda_n} = \frac{mv}{2L} = nf_1$ where $f_1 = \frac{v}{\lambda_1} = nf_1$

A standing wave is equivalent to two transverse waves moving in opposite directions. Both string and wind musical instruments depend upon standing waves. For strings, tension, mass and length all play a part.

$$v = \sqrt{\frac{F_T}{m/L}}$$

Example 13

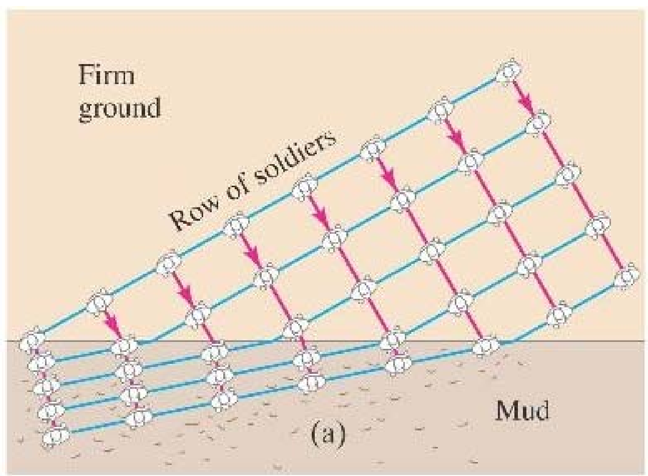
A piano string is 1.10 m long and has a mass of 9.00 g.

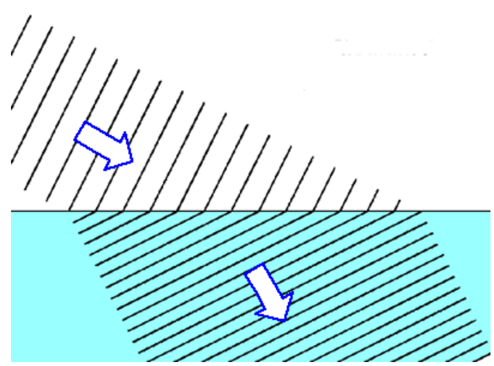
a) How much tension must the sting be under if it is to vibrate at a fundamental frequency of 131 Hz?

b) What are the frequencies of the first four harmonics?

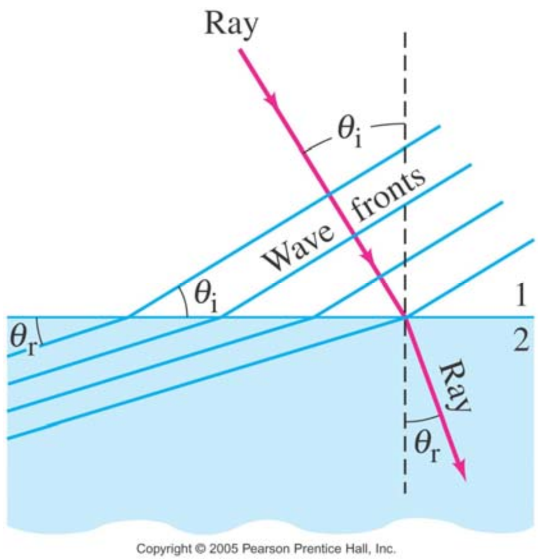
REFRACTION AND DIFFRACTION

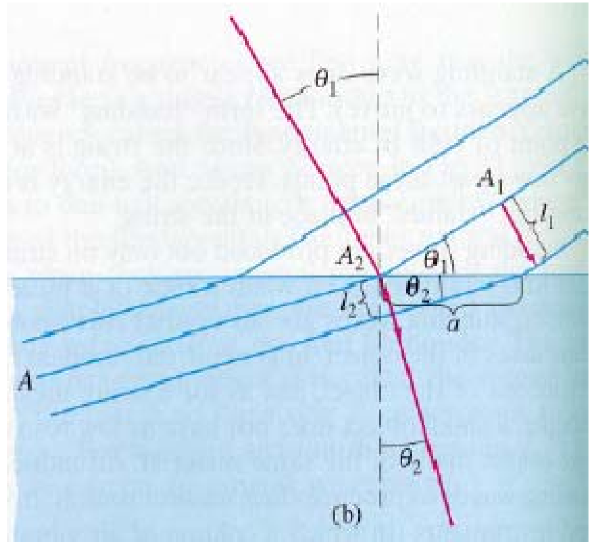
- **Refraction**--waves strike boundary, some of the energy is reflected and some is transmitted or absorbed; occurs when a wave traveling in one medium crosses a boundary; changes speed!
- To better understand, think about soldiers marching in formation on firm ground which gradually turns to mud.
- Or think about light waves as they pass through the atmosphere into the surface of a deep body of water.





Examine the diagrams below:





Shall we discuss the diagram on the far right? (Humor me!)

In the same time that wave A_1 moves a distance l_1 (don't go brain dead on me…the distance l_1 is equal to v_2t…we'll need that in just a minute), we see that A_2 moves a distance l_2. The two triangles shown have the side labeled *a* in common.

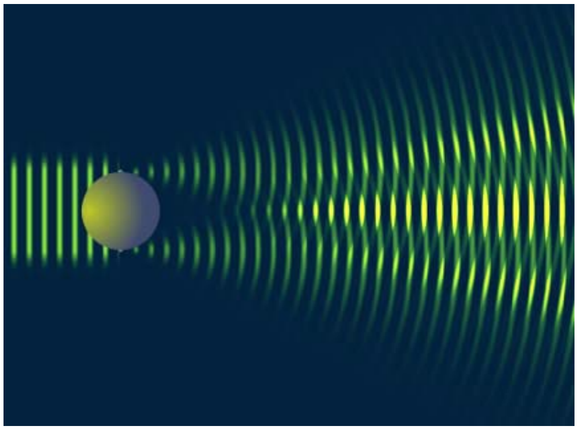
Thus, $\sin\theta_1 = \frac{l_1}{a} = \frac{v_1 t}{a}$ *and* $\sin\theta_2 = \frac{l_2}{a} = \frac{v_2 t}{a}$ which simplifies to a neat little mathematical relationship named the Law of Refraction (You didn't think reflection was going to have *all* the glory, now did you?)

LAW OF REFRACTION: $\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \frac{\sin\theta_r}{\sin\theta_i}$

Example 14

An earthquake P wave passes across a boundary in rock where its velocity increases from 6.5 km/s to 8.0 km/s. If it strikes this boundary at 30°, what is the angle of refraction?

- **Diffraction**—waves spread, encounter an object, bend around it somewhat and pass into the region behind.



- The image at right shows plane waves approaching an obstacle and the subsequent diffraction pattern.

- The amount of diffraction depends on the λ and size of the obstacle.

- If the λ is larger than the object, the wave bends as if the object was not there.

- If the object is larger, then a "shadow" region develops behind the object (like we see behind the sphere in the photo above). This concept applies to reflection as well.

- So waves with longer λ encountering larger objects result in more diffraction.

$\theta_{(radians)} = \frac{\lambda}{L}$ When energy is carried by material particles, it can't travel behind or bend around obstacles. If you stand around the corner of a building, you can't be hit by a baseball thrown from the other side, but you can hear a shout or see light bending around the building. Both interference and diffraction occur only for energy carried by waves and NOT for energy carried by particles. In other words, they are wave phenomena.