Physics 101 – Lecture 20
Waves & Sound

Recall we've talked about transverse & longitudinal waves:

- transverse waves: medium motion is $\perp$ to wave motion
- longitudinal (pressure) waves: medium motion is $||$ to wave motion

Wave speed on a cord:

$$v = \sqrt{(F_T/[m/L])}$$

Wave equation:

$$v = \lambda f$$

Energy transport by wave:

$$\text{Intensity} = \text{power/area} = 2\pi^2 f^2 v \rho A^2$$

Giancoli 11-58. A particular guitar string is supposed to vibrate at 200 Hz but vibrates at 205 Hz. By what percent should the tension be changed to correct the frequency?

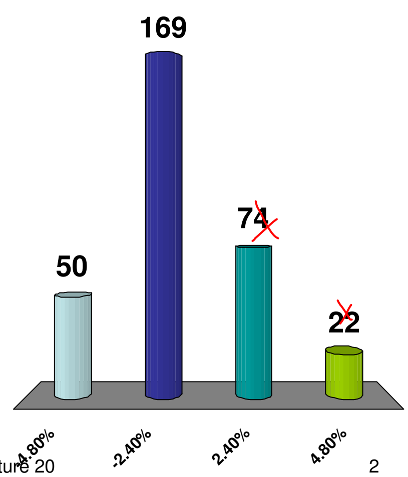
1. -4.8%
2. -2.4%
3. +2.4%
4. +4.8%

$v = \lambda f = \sqrt{F_T/(m/L)}$

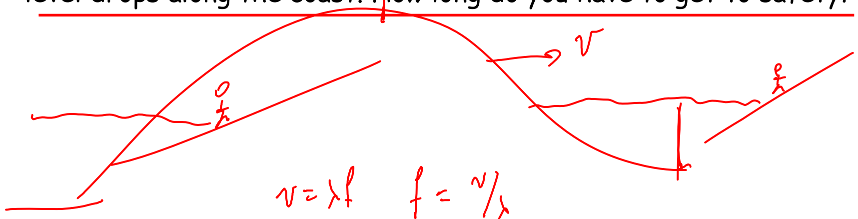
$f \sim \sqrt{F_T}$

$\frac{f_{new}}{f_{old}} = \frac{200}{205} = \sqrt{\frac{F_{T\,new}}{F_{T\,old}}}$

$\frac{F_{T\,new}}{F_{T\,old}} = \left(\frac{200}{205}\right)^2$



Example: Giancoli 11-67. A tsunami of wavelength 250 km and speed 750 km/h (typical values) approaches a coastline, and the water level drops along the coast. How long do you have to get to safety?



$v = \lambda f \quad f = v/\lambda$

$= 750\ \text{km/h} / 250\ \text{km}$

$= 3\ \text{hr}^{-1}$

$T = \frac{1}{3}\ \text{hr} = 20\ \text{min}$

10 min.

Wave phenomena:

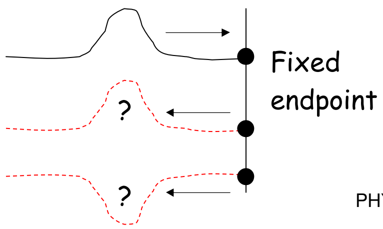
Waves show a host of phenomena that will interest us, including reflection, refraction, diffraction and interference. While these are commonly associated with light waves, they occur for ALL waves.

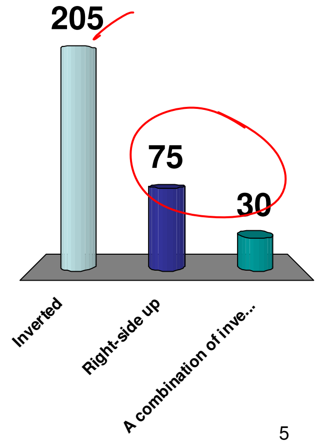
Waves can be reflected by obstacles or the end of the medium in which the wave is travelling. For example:

- a sound wave echoes (bounces) off a rock wall;
- a water wave will reflect off of a cliff-side;
- a wave on a rope will ‘bounce off’ the end of the rope:

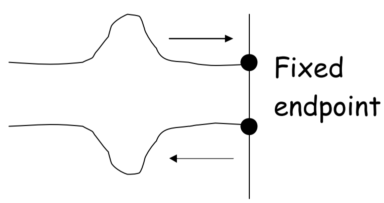
Consider a transverse wave on a string reflecting off of a fixed endpoint. The wave is …

1. Inverted
2. Right-side up
3. A combination of inverted and right-side up





The wave is inverted (there has been a change of phase of ½ of a full wave – ie, 180°)!

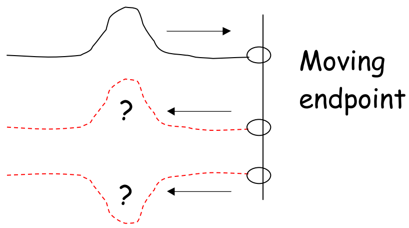


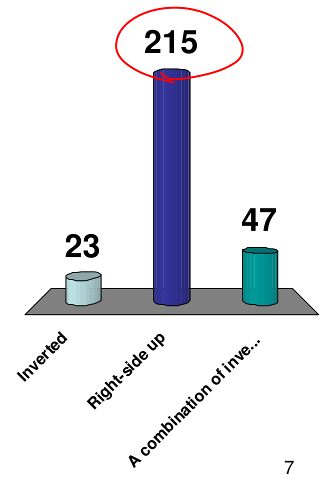
Change of phase!

general feature at many interfaces

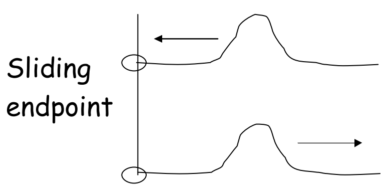
Consider a transverse wave on a string reflecting off of a moving endpoint. The wave is …

1. Inverted
2. Right-side up
3. A combination of inverted and right-side up



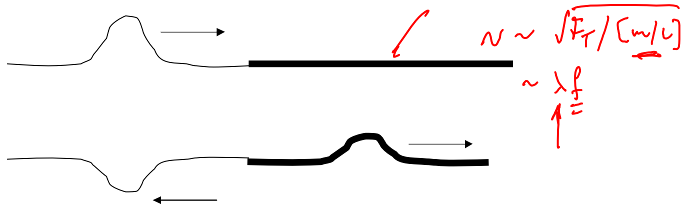


The wave is not inverted (no change of phase)!



No change of phase!

In fact, reflection occurs whenever the medium density changes. For example, if you join a section of light rope to a section of heavier rope, then there will in general be both reflection and transmission at the interface:

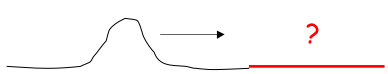


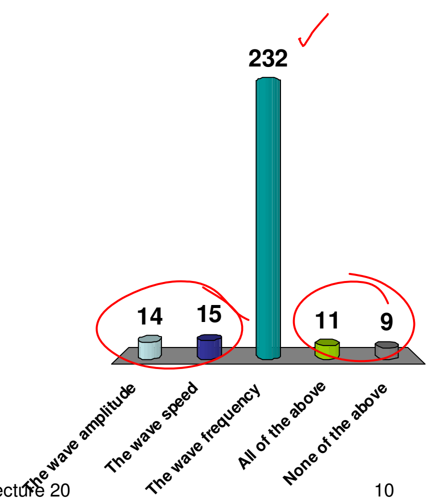
The frequency of the transmitted wave will be the same as the initial wave, but its wavelength and speed will be different, such that

$$f = v/\lambda$$

When a wave on a string hits a boundary with a section of the string having a different mass, which do you expect to be the same between the two sections of the string?

1. The wave amplitude
2. The wave speed
3. The wave frequency
4. All of the above
5. None of the above

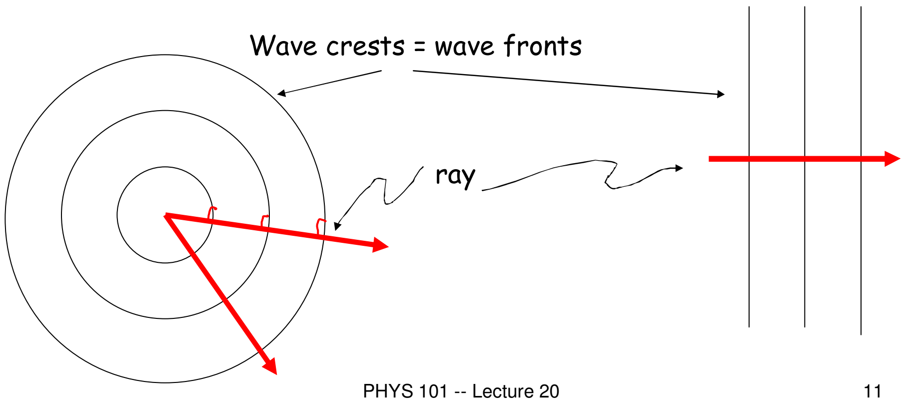




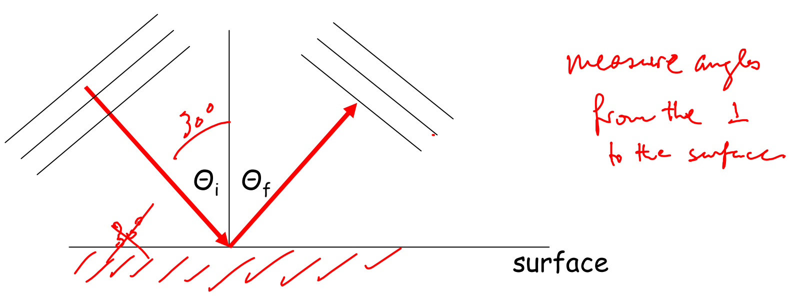
For 2- or 3-dimensional waves, the general rule at interfaces is that:

angle of incidence = angle of reflection

To measure these angles we consider rays, lines that cross wave fronts (such as wave crests) at right angles:



So reflection from a surface looks like this:



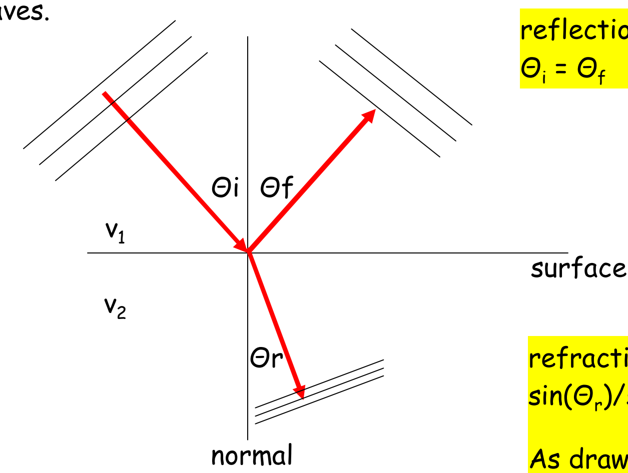
Angle of incidence = angle of reflection:

$\Theta_i = \Theta_f$

At a surface/interface we will also get some of the energy transmitted across the surface.

When the velocities of the waves in the 2 media are different, we also have refraction: a difference in direction of the incident and refracted waves.

reflection:
$\Theta_i = \Theta_f$

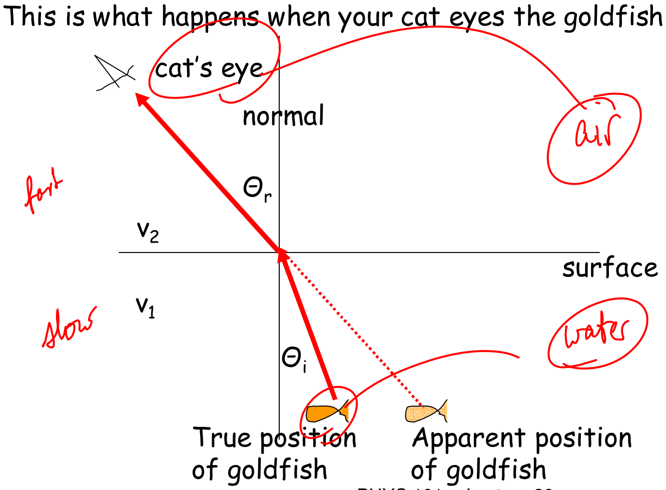


refraction:
$\sin(\Theta_r)/\sin(\Theta_i) = v_2/v_1$

As drawn: $v_2/v_1 < 1$

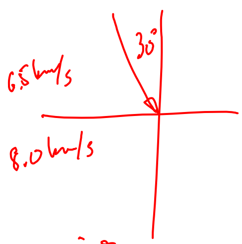
For example, if the wave goes from a material with a high wave velocity to a material with a lower wave velocity, then the wave will be refracted towards the normal.

This is what happens when your cat eyes the goldfish in your tank:

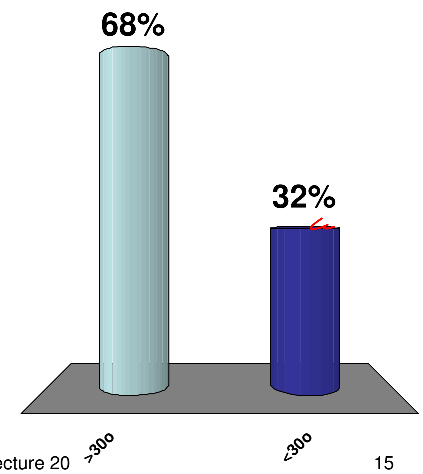


Giancoli Ex 11-15: Earthquake P-wave (pressure wave) passes rock boundary where v changes from 6.5 km/s to 8.0 km/s. If it strikes boundary at 30°, what is angle of refraction?

1. >30°
2. <30°



$\frac{\sin\theta}{\sin 30} =$



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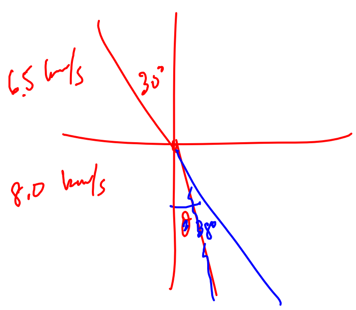


$\frac{\sin\theta}{\sin 30} = \frac{8.0}{6.5} > 1$ $\quad \sin\theta > \sin 30°$

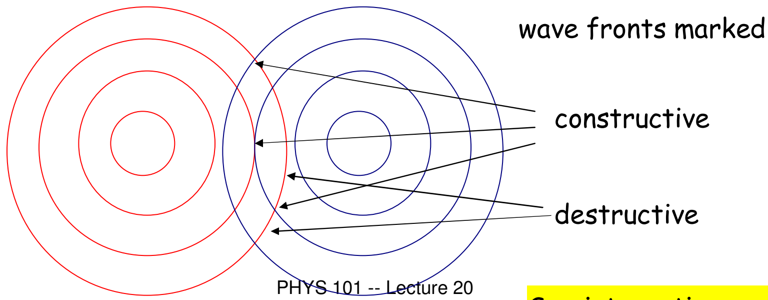
$\theta > 30°$ $\quad \sin\theta = 0.615$

$\theta = 38°$

Superposition of waves:

When two waves 'cross' we see the phenomenon of interference: the displacements of the particles in the waves are the sums of the displacements due to each wave. This is superposition.

Thus, two crests will add to give a new crest that is the sum of the old ones – constructive interference; two troughs will 'add' to give a new trough, and (if the amplitudes are the same) crests and troughs crossing will cancel – destructive interference.

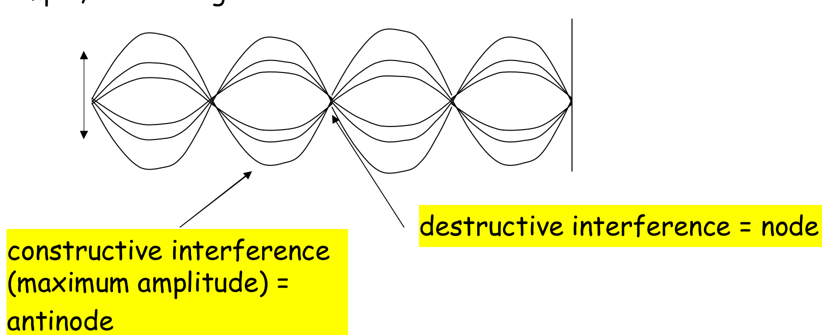


See interactive module

Standing waves & Resonance:

When we add waves together we can get a condition that we call a standing wave: a wave that doesn't appear to move. Instead, the wave appears to have a fixed pattern.

For example, on a string:



In fact, although the wave doesn't appear to move, we must have

$v = \lambda f$ (velocity of wave on string)

How can we reconcile these two ideas?

The standing wave is actually a superposition of two waves: one moving right, and one moving left.

On a string, the frequencies of standing waves are the resonant frequencies (or natural frequencies) of the cord. When we pluck the cord, many frequencies will be excited… but most will interfere and die out, leaving only the resonant frequencies.

The lowest of these will be the fundamental frequency, in which the only nodes are at the ends of the cord. The other natural frequencies are called overtones and correspond to adding one (or two, or 3, etc…) more nodes…

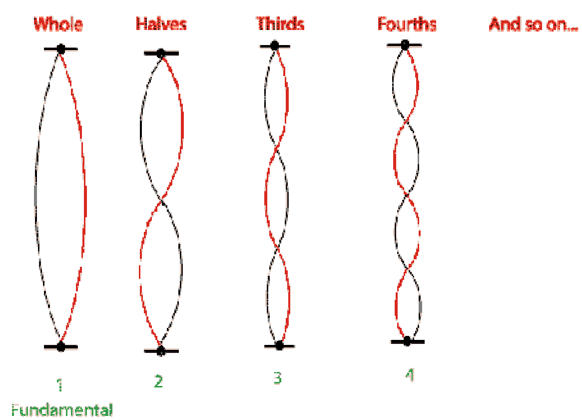
For a cord of length L, we have:

$L = \frac{1}{2} \lambda_1$

Where λ_1 is the wavelength of the fundamental. The general rule is:

$L_n = n\lambda_n/2$

where n is an integer n=1,2,3,4,…



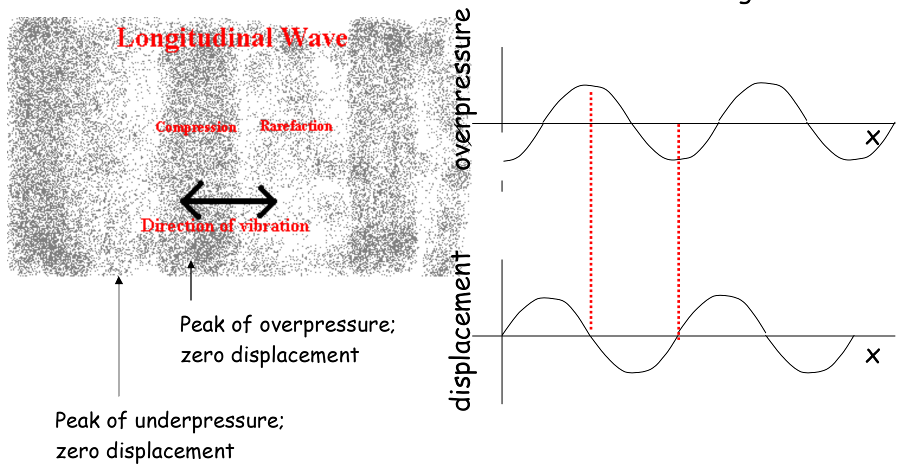
The frequencies are:

$f_n = v/\lambda_n = nv/2L$ (recall $v \sim \sqrt{(F_T/[m/L])}$)

For a plucked string these frequencies are multiples of the fundamental frequency and are called harmonics, with the fundamental called the first harmonic.

Sound

We've seen that sound is a wave: a longitudinal (or pressure) wave, where particle motion is in the same direction as the wave is moving.



Sound is generated by vibratory motion of many types: stretched strings (stringed instruments), membranes (for example, drums), columns of air (wind instruments), or vibrations of solid objects.

Sound consists of and requires these vibrations; in the absence of material (ie, a vacuum), sound waves do not exist or propagate.

The speed of sound in air is approximately 340 m/s (and is a function of humidity, density, and temperature), and is different in other materials:

helium:	~ 1000 m/s
water	~ 1500 m/s
solids	~ 4000-5000 m/s

Examples: measuring the distance to lightning strikes: t/3 = d [in km], listening to railway rails 'sing' as a train approachs.

Sound waves are characterized by two physical quantities that we've seen in our previous discussions: intensity & frequency.

Intensity → loudness.
Frequency → pitch.

Humans can perceive sounds ranging in intensity from

$$10^{-12}\ W/m^2 < I < 1\ W/m^2$$

(higher intensities can be painful and do physical damage to the ear), and over a frequency range (the audible range) of about:

$$20\ Hz < f < 20{,}000\ Hz = 20\ kHz$$

Frequencies above this range are called ultrasonic, and below this range are called infrasonic. Many animals are sensitive to sounds in these ranges (dogs' perception goes to beyond 50 kHz; whales communicate at very low frequency).

Loudness, Intensity, bels, and all that…

We measure loudness in units called bels, after Alexander Graham Bell. Decibels (dB) are used more frequently, and are of course, 1/10 of bels:

1 bel = 10 decibels (dB)

The range of human-perceivable loudness spans more than 12 orders of magnitude, and so it's not linearly related to intensity, but is an approximately logarithmic scale, with

x 2 loudness ≈ x 10 intensity

Not surprisingly, then, bels and decibels are defined logarithmically too: loudness (written β ["beta"]) is:

$$\beta\ [\text{in dB}] = 10 \log(I/I_0) \qquad [\text{log base-10}]$$

where I_0 is some reference: usually the threshold of audibility, $10^{-12}\ W/m^2$

Note that because of the way logarithms work, an increase of, say, 20 dB is always an increase of intensity of a constant factor:

+ 20 dB → log (I/I_0) increasing by 2
= I/I_0 increasing by 10^2
= I increasing by 10^2 for given I_0

Some examples of loudness levels:

threshold of pain:	~ 120 dB
Loud siren at 30m	~ 100 dB
Normal conversation	~ 60-70 dB
Whisper	~ 20 dB

Example: Giancoli Ex. 12.3 What is the sound intensity on a street if the noise level is 70 dB ?

Example 2: Giancoli 12.17: Humans can detect a difference in sound level of 2 dB. What is the ratio of amplitudes of the two sounds?

Giancoli 11.63: Water waves approach an underwater shelf where velocity changes from 2.8 m/s to 2.1 m/s. If the incident wave makes an angle of 34^{o} with the shelf, what is the angle of refraction?