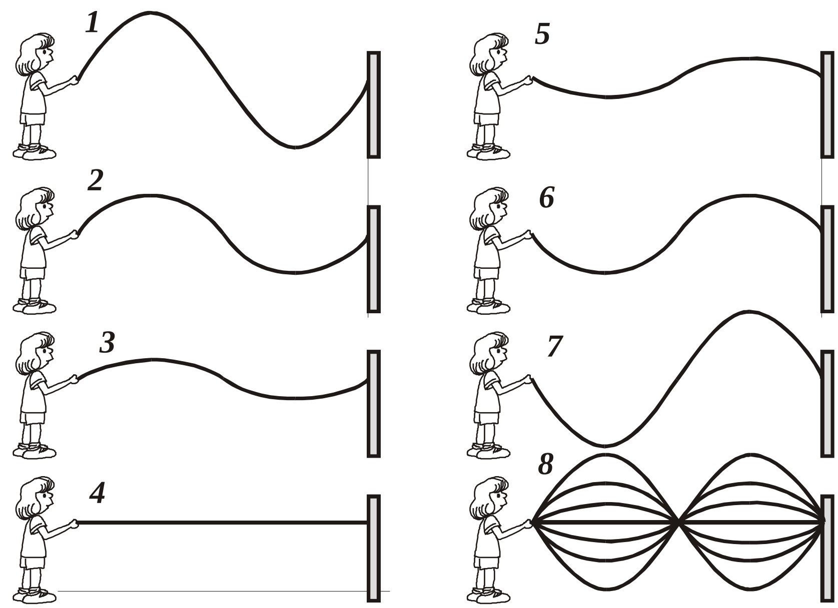
AP Physics – Standing Waves & Harmonics

Standing waves: If you take a long, slinky spring and fix one end of it to a wall and then shake the free end you produce a pulse that travels down the spring. The pulse will be reflected when it reaches the end of the spring, and if at the right frequency it will produce a standing wave as shown in class. The incident wave and the reflected wave will alternately interfere with each other constructively and destructively. The effect is that parts of the spring will not move at all and other parts will undergo great motion.

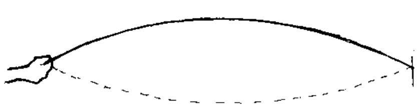


Time Lapse View of Standing Wave

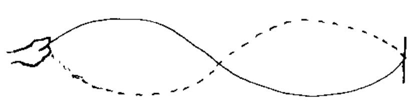
Referring to the demo in class, the parts of the wave that don't seem to be doing much are called the __________________ and the places where the wave is undergoing ____________________________________ are called ____________________________. The end of a string with such a wave that is ______________________ to the wall would have to be a ________.

You can produce a ____ by __________________________ the _________________________ of the wave. You will have seen a delightful demonstration of standing waves in action.

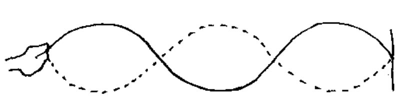
Musical instruments produce standing waves. Piano strings, the interior of a tuba, a flute, and violin strings all produce standing waves. Buildings being buffeted about by the wind also have standing waves. Both _______________________________ & ______________________________ waves can _____________ ____________________________________.



The standing wave to the left represents _____ of the ____ of the wave (you only see the crest here).



This would be a complete wave cycle or ______ (you see a crest and trough)

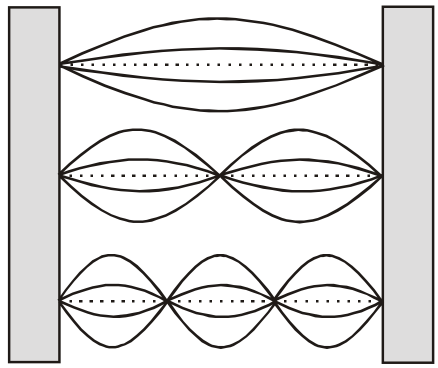


This would be ________ or 1 ½ wave (you see 2 crest & 1 trough).

The ________________________________ standing wave for a system is called the _____________________ frequency or the ___________________________________.

Fundamental Frequency ≡ Lowest frequency of vibration

_________________ multiples of the fundamental frequency are called ___________________________. The first harmonic is the fundamental frequency. The _______ harmonic is simply _______ the ______________________________ frequency. The third harmonic is three times the fundamental harmonic. And so on.



Natural Frequency: Every object has a natural frequency at which it will vibrate. How loud this sound is depends on the elasticity of the material, how long it can sustain a vibration, how well the whole object can vibrate, how big it is, etc. Some materials vibrate better than others. For example, a piece of metal, if excited (say you hit it with something), will vibrate. The vibrations will spread throughout the piece and the whole thing will vibrate. Think of a bell. On the other hand, a piece of Styrofoam, to look at the other extreme, is not nearly so good at vibrating. You can bang on it all day and get nothing better than the odd dull thud kind of sound. So bells are made of metal and not polystyrene foam. At any rate when you bang on an object, it will vibrate at its natural frequency. This principle is used in many musical instruments.

Forced Vibrations: A tiny little speaker will produce sound. Speakers have a small coil that is made to vibrate by the electrical output of an amplifier. Attached to the coil is a paper cone. The vibrating coil then forces the paper cone to vibrate. Air molecules in contact with the speaker cone are then force to vibrate which creates sound waves in the air. These waves travel through the air to your ears. The cone in a speaker has a very small area and usually does not do a very good job of transferring the sound energy into the air. So it sounds lousy and weak. Get a bigger cone and it will do a better job of sending out sound waves.

Forced vibration = The vibration of an object that is made to vibrate by another vibrating object in contact.

Example: A tuning fork makes a very weak sound - you can barely hear the thing. Place a vibrating tuning fork against a window or desktop, however, and the sound will become much louder.

Interesting Fact => People do not recognize their own voice. Have you ever heard a tape recording of your voice? Did it sound like you? Probably not. This is because the sounds that you make travel to your ears via your skull and not through the air. The vibrations that reach your ear through your bones and tissue sound slightly different than the vibrations that travel through the air.

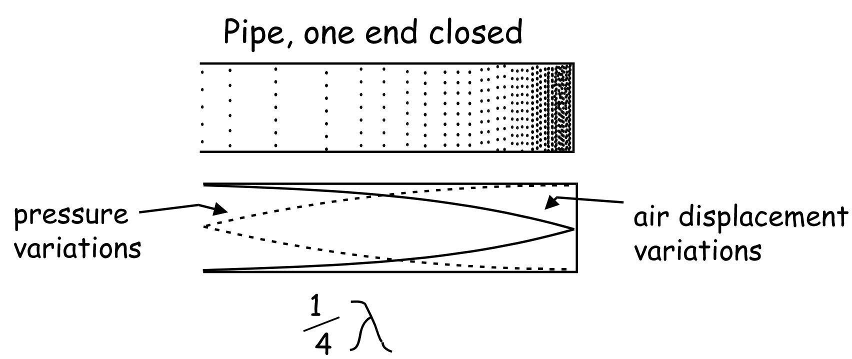
Forced vibration is very important in music. Many instruments have sounding boards which are forced to vibrate to make the instrument sound louder - pianos are a good example of this. Other instruments have bodies that act as sounding boards. Guitars, violins, banjos, mandolins, and ukuleles fit into this category. The vibrating strings of these instruments produce a very pitiful weak sound, but place the same string on your average Martin guitar, and you get a whole different deal. Much of what makes up the quality of sound produced by an instrument depends on how well it can transfer sound energy into the air. We've all heard of these fabulous old violins from Italy - the best known are the Stradivarius violins - which produce really exquisite sound. Modern violinists claim that no modern violin can even come close to the quality of sound that these violins produce. So a Stradivarius violin can sell (if anyone is willing to sell theirs) for millions of dollars. How these violins were made - the secret that gives them their rich sound is not known. All sorts of people are desperately trying to duplicate the feat, but so far, no one has succeeded.

Resonance : The word '______________________' means "resound and is sometimes called ***sympathetic vibration***. It means to "________________________" or "___________________________". If two objects which have the same natural frequency are placed near each other, and one is set to vibrate, the other one will begin to vibrate as well.

What happens is that the first instrument forces the air to vibrate at its natural frequency. These sound waves travel to the other object and causes it to vibrate at that very frequency. But this is also its natural frequency. So the waves induce a vibration. Each compression arrives in phase with the vibrations of the object and adds to its energy, and causes it to build up. So the second object will begin to vibrate and then vibrate stronger and stronger.

A common demonstration of resonance can be done with a book. The book is hung from a bar. A person applies a puff of air to the book, causing it to swing a little. When it comes all the way back from the swing, another puff is applied. It swings just a bit farther out. Apply yet another puff, it swings more. Eventually you get the book to really swing. What you are doing is applying energy at the resonant frequency of the system. So the motion builds up and becomes greater and greater. For this to happen, however, the energy must be fed in at the resonant frequency of the object. We can associate these resonant waves with standing waves in the object. If you blow randomly, this will not work.

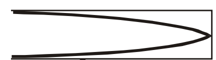
Resonant Air Columns: Have you ever blown into a pop bottle and gotten the thing to make a nice, deep, melodious sound? Bottles can do this because they will resonate. When you blow across the top of the bottle, you create turbulence – burbles of air – which occur at a broad band of frequencies. This is called the edge effect. One of those frequencies is the bottle's resonant frequency. A _______________________________________ __________________ in the bottle's interior. As energy is fed in from the blowing thing, the standing wave ___________________________ until it is loud enough to _______________.



Close Ended Pipes: The reason that the bottle resonates is that a standing wave forms in it. The ___________________________ of the standing wave has to "________________________________", so only the _____________________________ (or its ___________________________) will ____________________ and be heard. The other frequencies aren't loud enough to be audible. ***The _____________________________ of the pipe is a displacement _____________*** because the wall does not allow for the longitudinal displacement of the air molecules. As a result***, the reflected sound pulse from the closed end is 180° out of phase with the incident wave***. The ___________________________ corresponds to a pressure __________________________.

The ***open end of the pipe is, for all practical purposes, an antinode***. The reflected wave pulse from an open end of the pipe is reflected in phase. The open end of a pipe is essentially the atmosphere, so no pressure variations take place. The reflection actually takes place a slight distance outside the pipe, but we will ignore that.

Let's look at a simple pipe that has a standing wave within it. There has to be a displacement node at the closed end and a displacement antinode at the open end. With this in mind, we can draw in the various standing waves that can form within the pipe. The first one is a quarter of a wave. This is the lowest resonant frequency that can form a standing wave in the tube. Note that the closed end reflects the sound wave out of phase - like a fix-ended wave is reflected.



First harmonic

Third harmonic

Fifth harmonic

Anyway, the ___________________________ turns out to be about _____ of the ____. The lowest frequency is called the fundamental frequency. Its wavelength is essentially ¼ of the length of the pipe.

The next possible frequency will have a wavelength that is ____ of the pipe's length, then _____ of the length, and so on. You can see that only _______________________________ are resonant in the _______________________________ pipe.

Only the odd harmonics are present in a resonating close-ended pipe.

The equation that relates wavelength, frequency and wave speed is:

For the fundamental frequency (the first harmonic), the wavelength is:

The frequency in the system must be:

If we want the frequency of the third or fifth or whatever harmonic, we would get:

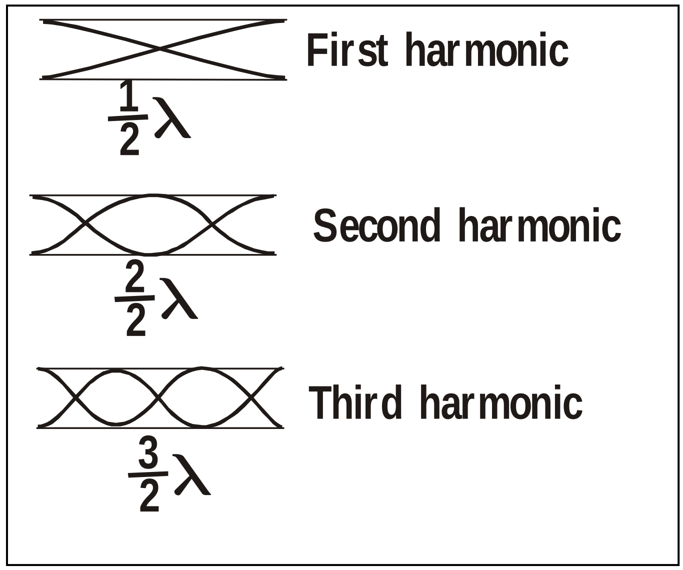
** This equation is NOT given on the AP Exam

Here f_n is the harmonic frequency that resonates in the pipe, v is the speed of sound, L is the length of the pipe, and n is an integer for the harmonic that you want.

The wavelength for any harmonic would be: $\lambda_n = \frac{4l}{n}$ $\quad n = 1, 3, 5, \ldots$

Open Ended Pipes: Open-ended pipes can also resonate. At both ends of the pipe, the wave is reflected in phase. The fundamental wave and associated harmonics would look like this:

The ________ is approximately _______ the length of the ___________. Note also that the ***open ended pipe has*** _________________________________ ***present***.



Using the same method of derivation as we did with the close-ended pipe, we can develop an equation for the wavelength for the fundamental frequency.

Here is the equation. See if you can derive it yourself.

A critical difference between the open and close-ended pipes is that the open-ended pipe can have all harmonics present. The close-ended pipe is limited to the odd harmonics.

All harmonics can be present in a resonant open-ended pipe.

Example Problems:

1) A pipe is closed at one end and is 1.50 m in length. (a) If the sound speed is 345 m/s, what are the frequencies of the first three harmonics that would be produced? (b) How many harmonic frequencies of this pipe lie in the audible range, from 20 Hz to 20,000 Hz? (c) What are the 3 lowest possible frequencies if the pipe is open on both ends?

(a) Use the close ended pipe formula to find the first harmonic (the fundamental frequency):

(b) Recall that close ended pipes only have the odd harmonics, so the next two would be the third and fifth harmonics:

(c) Now the pipe is changed to open on both ends so what happens to n?

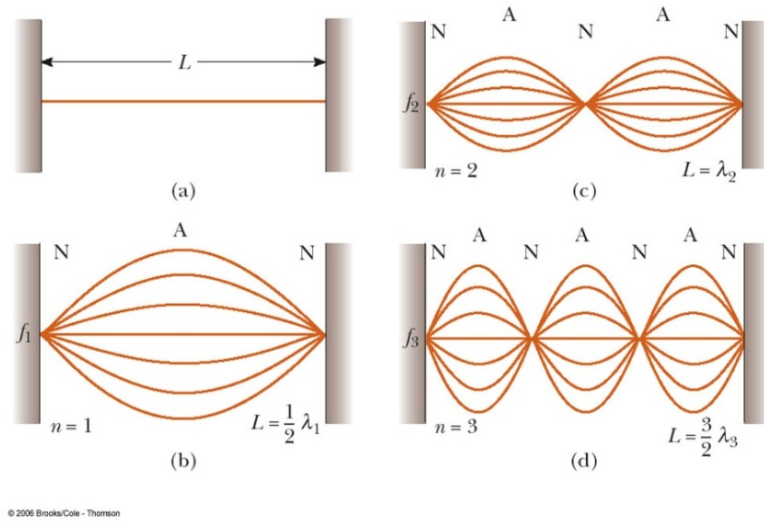
2. (a) What length pipe open at both ends has a fundamental frequency of 370 Hz? Find the first overtone. (b) If the one end of the pipe is now closed, what is the new fundamental frequency? Find the first overtone. (c) If the pipe is open at one end only, how many harmonics are possible in the normal hearing range from 20 to 20,000 Hz?

(a)

(b)

(c)

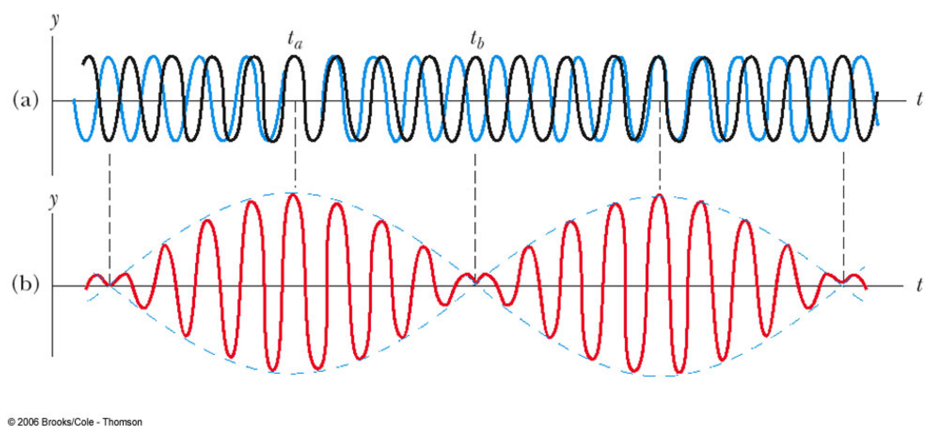
String Instruments: Look at the diagram to the right, does this look similar to an open ended pipe or one that is closed on one side?



A pipe open on both ends has an antinode at each end and this ________________________ have a ________________ on ______________ __________________. It looks different but mathematically its similar to a pipe open on both ends. So you can use:

$$f_n = n\frac{v}{2L} \qquad n = 1, 2, 3, \ldots$$

Beats: Beats are ________________________________ in ______________________________, due to ________________________________. Waves have slightly different frequencies and the time between constructive and destructive interference alternates. The beat frequency equals the difference in frequency between the two sources.



$$f_b = |f_2 - f_1|$$