AP Physics - Sound

Sound is a longitudinal mechanical wave. For most of the time, what we will be talking about is a wave that travels through air. Sound can travel through other mediums - water, other liquids, solids, and gases. We can hear sounds that travel through other mediums than air – put your ear to the wall and hear the sounds on the other side. You hear sounds when you are under water - although not as well as in air. This is because our ears are set up for listening to sounds that move through the atmosphere.

The disturbance which travels through air is the compression of air molecules – they are squeezed together and pulled apart. Sound is a series of traveling high pressure and low pressure fronts.

Sound waves are frequently graphed with pressure on the $y$ axis and time on the $x$ axis. This makes the wave look like a transverse wave - a sine wave shape on the graph. But in this depiction, changes in pressure are being plotted Vs time and it is not a depiction of the disturbance itself, which is longitudinal.

Here we see a graph of pressure Vs time. The compressions are regions where the air pressure is greater than the ambient pressure of the air. The rarefactions are areas of lower pressure. These high and low pressure ridges travel outward in an expanding sphere from the sound source.

The sound source is simply something that vibrates. It can be the clangor on an alarm clock, a window shade flapping in the wind, or your vocal cords vibrating because air is passing through them. The vibrating sound source collides with air molecules, causing them to scrunch together and...
pull apart. These scrunches travel through the air. But the air molecules do not physically travel across the room. They are excited by the sound source and gain kinetic energy. They move outward and have elastic collisions with other air molecules, which then gain energy, and so on.

The damping of a sound wave (decrease in amplitude) as it travels is called **attenuation**. Attenuation depends on the medium and the frequency of the sound. Low frequency sounds are attenuated less than high frequency sounds. Whales make very low frequency sounds (in the neighborhood of 1 - 10 Hz) which can travel hundreds of miles through the ocean. It has recently been found that elephants also employ similar low frequency sounds to communicate. In air, these sounds can travel many miles.

**Audible Spectrum:** The human ear is not the world's best sound receptor, although it does all right (if you take care of them). A typical person can hear sounds whose frequency ranges from 20 Hz to about 20 000 Hz. This is known as the **audio spectrum**. Sounds with a higher frequency are called **ultrasonic** sounds and sounds of a lower frequency are called **infrasonic** sounds.

Other animals have different hearing spectrums. Dogs can easily hear sounds up to 45 000 Hz. Whales and elephants hear very low frequency sounds (below 10 Hz).
The Doppler Effect: Imagine a water bug floating motionless on the surface of a calm pond on a lovely summer day. The bug, bored out of its little bug brain, is tapping the water with a pair of its little segmented legs, making a series of waves that radiate outward on the surface - like the ripples on a pond (actually, they are ripples on a pond, ain't they? Curious, what?). The bug is unwittingly producing a traveling wave. It would look like this:

The waves spread out in all directions. The distance between the wave crests is the wavelength, \( \lambda \). This wavelength is the same in all directions. Now, imagine that the bug starts swimming in one direction, but it still makes its little periodic vibrations with its legs at a constant frequency. We would see a different wave pattern.

Notice that the waves in front of the bug are pushed closer together. Behind the bug, the waves are stretched further apart. The waves in front have a shorter wavelength, the waves to the rear have a longer wavelength. Since the speed of the wave is a constant and equal to the wavelength multiplied by the frequency, this means that the frequency of the waves traveling in front of the bug is higher. The waves behind the bug are lower in frequency. We call this frequency change the Doppler shift or the Doppler effect.

This happens because the bug makes a wave and then swims after it. So that, when he makes the next wave, it will start out closer to the first wave and so on. As the wave travels to the rear, it is already further away from the first wave, so the wavelength is longer and the frequency shorter. All the waves travel at the same speed so they can't make up the difference.

What happens if the bug swims at the same speed as the wave?

The bug is making a wave and then moving right along with it. So the bug is riding on top of the wave. Then the bug makes another wave that is on top of the first, and so on. The bug ends up riding an enormous wave because all the wave crests are in phase and add up. This would be tough swimming for the old water bug.
What happens if the bug swims faster than the waves?

The bug makes a wave and swims through it into clear water, then it makes the next wave, and so on. The bug is always in front of the waves in nice smooth water. The waves propagating behind the bug will have their crests in phase along a line to either side of the bug that trails back from the bug - they sort of overlap. They will constructively interfere with each other and form a V shaped bow wave. The bow wave will have a very large amplitude as it spreads out behind the bug. Boats and ships do this all the time. Many harbors have speed limits for ships because if the ship travels too fast it will generate a large bow wave that can damage property on either side of the vessel.

Doppler Shift and Sound: Sound, like all waves, undergoes this Doppler shift. A car moving towards you pushes its sound waves closer together in front so the sound you actually hear has a higher frequency. When it moves away from you its frequency is lower. You can hear this change when you are near traffic. You can listen to a car and tell from the change in pitch when it stops coming toward you and starts moving away.

In order to experience the Doppler shift, there must be relative motion between the sound source and the listener.

If there was no motion between the sound source and the listener, then this equation would hold true:

\[ v = f \lambda \quad \text{so} \quad f = \frac{v}{\lambda} \quad \text{and} \quad \lambda = \frac{v}{f} \]

But there is motion between them. What happens when the listener is moving towards the sound source?

The frequency heard must be:

\[ f' = \frac{v'}{\lambda} = \frac{v + v_0}{\lambda} \]

The velocity is the sum of the velocity of the listener and the speed of sound.

We know that the wavelength is given by:

\[ \lambda = \frac{v}{f} \]

We can plug that into the equation we’ve derived for the new frequency:
\[ f' = \frac{v + v_0}{\lambda} = \frac{v + v_0}{\left(\frac{v}{f}\right)} = f\left(\frac{v + v_0}{v}\right) \]

So the new frequency heard by a moving listener closing on a stationary sound source is given by:

\[ f' = f\left(\frac{v + v_0}{v}\right) \]

\(f'\) is the new frequency heard, \(f\) is the frequency actually produced, \(v\) is the velocity of sound, and \(v_0\) is the velocity of the listener.

If the listener is moving away from the sound source. It is obvious that the new frequency is given by:

\[ f' = f\left(\frac{v - v_0}{v}\right) \]

But what about if the sound source is moving and the listener is stationary?

If the sound source is moving towards the listener, the wavefronts that arrive at the listener are closer together because of the motion of the sound source. The wavelength measured by the listener is shorter than the wavelength that is actually produced by the sound source. Is this clear? Think about it and do not proceed until the previous statement is clear.

So \(\lambda'\) (wavelength collected by listener) is shorter than \(\lambda\) (wavelength that is produced). Each vibration or cycle takes a time that is the period of the wave, \(T\). During this time \(T\), the source moves a distance of;

\[ v = \frac{x}{t} \quad x = v_s t \quad \text{Since the time is the period we get:} \]

\[ x = v_s t = v_s T \]

The period and frequency are related by:

\[ T = \frac{1}{f} \]

We can put this together with the equation for distance and we get:

\[ x = v_s T = v_s \left(\frac{1}{f}\right) \quad x = \frac{v_s}{f} \]
The distance is the change in wavelength, so we can write this as: \( \Delta \lambda = \frac{V_s}{f} \)

This is the change in wavelength that the listener observes.

The observed wavelength, the one the listener measures is the original wavelength minus the change in wavelength:

\[ \lambda' = \lambda - \Delta \lambda \quad \lambda' = \lambda - \frac{V_s}{f} \]

Because \( \lambda = \frac{V}{f} \)

We can write \( \lambda' = \lambda - \frac{V_s}{f} \) \( \frac{V}{f} = \frac{V}{f} - \frac{V_s}{f} \)

We can solve for \( f' \):

\[ V = \left( \frac{V}{f} - \frac{V_s}{f} \right) f' \quad Vf' = (V - V_s) f' \quad \left( \frac{V}{V - V_s} \right) f = f' \]

So, cleaning it up a bit, we get:

\[ f' = f \left( \frac{V}{V - V_s} \right) \]

\( f' \) is the frequency heard, \( f \) is the original frequency, \( V \) is the speed of sound, and \( V_s \) is the speed of the sound source.

If the sound source is moving away from the stationary listener, the equation becomes:

\[ f' = f \left( \frac{V}{V + V_s} \right) \]

When solving Doppler problems, we will assume that the speed of sound is 345 m/s.

- A train is traveling at 125 km/h. It has a 550.0 Hz train whistle. What is frequency heard by a stationary listener in front of train?

First, convert the train’s speed to meters per second:
\[ \frac{125 \text{ km/h}}{1 \text{ km/h}} \left( \frac{1 \text{ km}}{3600 \text{ s}} \right) \left( \frac{1000 \text{ m}}{1 \text{ km}} \right) = 34.72 \frac{\text{m}}{\text{s}} \]

Then plug the data into the equation which you will have derived (as above). Make sure to use the proper sign. In this case the train is closing on the listener, so the negative sign is selected.

\[ f' = f \left( \frac{v}{v - v_s} \right) = 550.0 \text{ Hz} \left( \frac{345 \frac{\text{m}}{\text{s}}}{345 \frac{\text{m}}{\text{s}} - 34.72 \frac{\text{m}}{\text{s}}} \right) = 612 \text{ Hz} \]

**Dubious Facts:**

- According to ancient Chinese astrologers, 70% of omens are bad.
- Airports that are at higher altitudes require a longer airstrip due to lower air density.
- Blue is the favorite color of 80% of Americans.
- California has issued 6 drivers licenses to people named Jesus Christ.
- Deaf people have safer driving records on average than hearing people in the U.S.A.
- Five percent of the people who use personal ads for dating are already married.

**Supersonic travel:** Supersonic motion means that the speed is greater than the speed of sound. (Figure that sound travels at 345 m/s.) In the past when one talked about supersonic motion, one was talking about flight, this is because airplanes were the main things that went faster than sound. (Bullets and projectiles also travel faster than sound.) That is no longer true as in the past few years goofy daredevils have managed to build cars that travel faster than sound. This was hard to do because the speed of sound is greater at the earth’s surface than it is at high altitudes.

Supersonic motion is a lot like the deal with the bug swimming faster than the waves it makes. Supersonic airplanes fly faster than the speed of sound, so the sound the plane makes expands outward as do all sounds from a sound source, except that the sound source is always in front. The effect is to form a “sound wake” where the compressions of the sound are constructively reinforced. This creates a “cone” of sound energy that trails behind the aircraft. This cone packs a lot of sound energy, so when it goes by a listener, a really loud, intense sound is heard. This sound wake thing is called a shock wave or sonic boom. Sonic booms can break windows, scare babies and animals, and crack mirrors. For this reason, airplanes are not allowed to go faster than sound over populated areas.
Resonance: The word ‘resonance’ means “resound”. This is an important topic with physics – let’s develop the thing a bit.

One of the goofy demonstrations the teacher performed involved a tiny little speaker. It was the cheapest and smallest speaker that he could find. When it was hooked up to a tape player, the sound quality was terrible. It sounded tinny and weak and really lousy - suitable only for rap music. But then the teacher pulled out a big piece of cardboard that had a small hole in it. He held the speaker up to the hole and suddenly the sound was ever so rich and nice and much louder too! So how come that happened?

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 – xylophones immediately come to mind.

Forced Vibrations: The tinny little speaker did produce sound – bad as it was. Speakers have a small coil that is set to vibrating 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 set to vibrating which creates sound waves in the air. These waves travel through the air to your ears. The cone in this cheap speaker has a very small area and does not do a very good job of transferring the sound energy into the air. So it sounds lousy and weak.

When the big piece of cardboard was brought out and the speaker was pressed onto it, the speaker forced the cardboard to vibrate. Since it was mechanically connected to the cardboard, the vibrations were easily transferred. The cardboard had a very large area in contact with the air, so it
was more efficient at sending the sound into the air. This is why the sound suddenly sounded so
much better when the cardboard made its appearance.

We call this phenomenon **forced vibration**.

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

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.

Another example of this that you experienced was the coat hanger on a string deal. When the
clothes hanger was hung from a piece of string and struck with something, you couldn’t really hear
anything (unless you placed your ear very close to the hanger). But if you pressed the string into
your ear, you heard a deep resonant gong/bell type sound when the hanger was tapped. The string
was forced to vibrate and conducted the sound to your ears.

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. At least
according to the music experts.

**Resonance Discussed:** Resonance is sometimes called sympathetic vibration. It means to
"re sound" or "sound again". 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.

The other interesting thing is that you can do it at a harmonic frequency. Blow every other swing or every third swing. Do you see how this would work?

**Resonant Air Columns:** Have you ever blown into a pop bottle and gotten the thing to make a nice, deep, melodic 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 standing wave forms in the bottle’s interior. As energy is fed in from the blowing thing, the standing wave gains energy until it is loud enough to hear.

**Close Ended Pipes:** The reason that the bottle resonates is that a standing wave forms in it. The wavelength of the standing wave has to "fit the bottle", so only the one frequency (or its harmonics) will resonate and be heard. The other frequencies aren’t loud enough to be audible. The closed end of the pipe is a displacement node 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 closed end corresponds to a pressure antinode.

The open end of the pipe is, for all practical purposes, a displacement antinode and a pressure node. 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.

Anyway, the pipe length turns out to be about ¼ of the wavelength. 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 $\frac{3}{4}$ of the pipe's length, then $\frac{5}{4}$ of the length, and so on. You can see that only odd harmonics are resonant in the close-ended pipe.

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

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

\[ v = f \lambda \]

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

\[ \lambda = 4l \]

The frequency in the system must be:

\[ v = f \lambda = f (4l) \quad f = \frac{v}{4l} \]

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

\[ f_n = n \frac{v}{4L} \quad n = 1, 3, 5, \ldots \]

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 wavelength is approximately twice the length of the tube. Note also that the open ended pipe has all harmonics 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.
\[ f_n = n \frac{v}{2L} \quad n = 1, 2, 3, \ldots \]

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.**

- A pipe is closed at one end and is 1.50 m in length. If the sound speed is 345 m/s, what are the frequencies of the first three harmonics that would be produced?

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

\[ f_1 = \frac{v}{4L} \]

\[ f_1 = 345 \text{ m/s} \left( \frac{1}{4 \left( 1.50 \text{ m} \right)} \right) = 57.5 \text{ Hz} \]

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

\[ f_3 = n \left( f_1 \right) = 3 \left( 57.5 \text{ Hz} \right) = 172 \text{ Hz} \]

\[ f_5 = n \left( f_1 \right) = 5 \left( 57.5 \text{ Hz} \right) = 288 \text{ Hz} \]

Musical instruments play things we call notes. A note is a specific frequency from a thing called a scale, which is a collection of eight notes called an octave. The notes are: A, B, C, D, E, F, and G. A C, for example, on some scales is 262 Hz. The interesting thing is that if you multiple the frequency of a note, you get the same note, but it is a higher harmonic. When you play a 262 Hz tone and a 524 Hz tone at the same time, they would give you the same musical sense, but would sound richer and fuller. The reason that different musical instruments sound different – think piano and mandolin, even when they are playing the same note, is that each instrument has its own set of harmonics. Some instruments only produce a fundamental frequency – flutes often do this, while other instruments produce a bunch of harmonics.

In the examples below, you see a pressure Vs. time graph for different things and instruments. A tuning fork, the first example, produces a single frequency, so its graph resembles a sine wave.

The flute and clarinet do not appear to be sine waves. This is because of the presence of harmonics and the law of superposition.
The last graph (above) shows the intensity of the different harmonics for the same instruments. The tuning fork only has the first harmonic. The flute has a strong 2nd and 4th harmonic. These are stronger than the fundamental frequency. The clarinet has a strong 5th and 1st harmonic. This is why they each sound different to our ears.