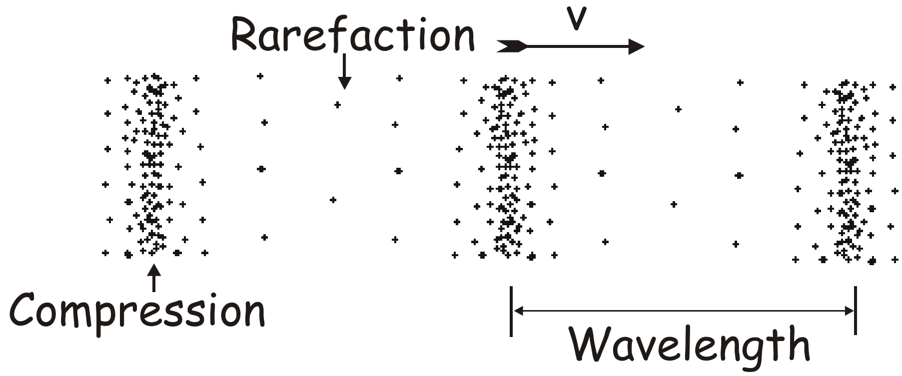
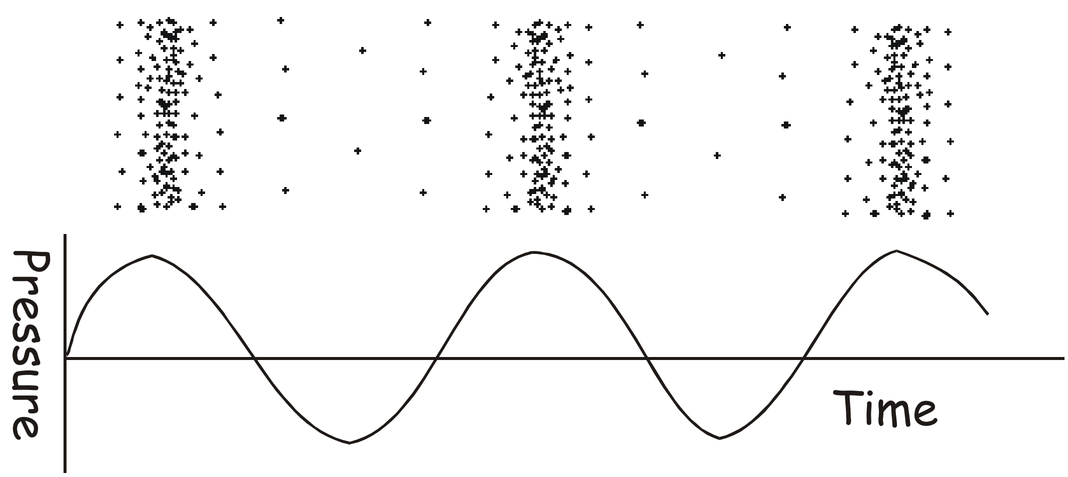
AP Physics - Sound

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.



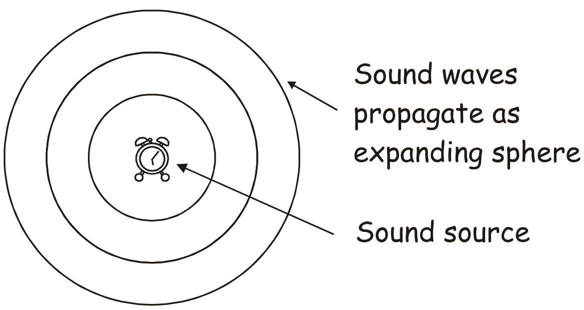
The disturbance which travels through air is the compression of air molecules – they are squeezed together and pulled apart. Sound is a series of traveling high pressure and low pressure fronts.

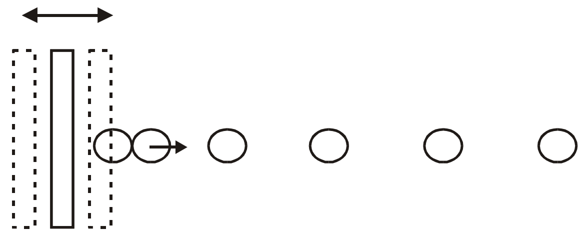
Sound waves are frequently graphed with pressure on the ***y*** axis and time on the ***x*** axis. This makes the wave look like a transverse wave - a sine wave shape on the graph. But in this depiction, changes in pressure are being plotted Vs time and it is not a depiction of the disturbance itself, which is longitudinal. So please, the Physics Kahuna begs of you, don't be confused about the thing.



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

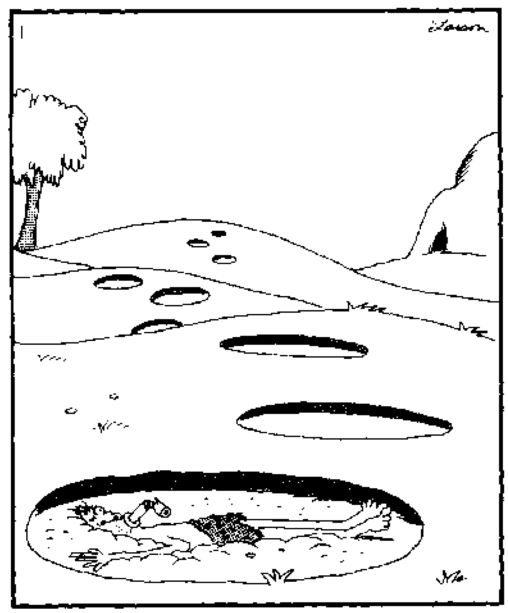
them. The vibrating sound source collides with air molecules, causing them to scrunch together and pull apart. These scrunches travel through the air. But the air molecules do not physically travel across the room. They are excited by the sound source and gain kinetic energy. They move outward and have elastic collisions with other air molecules, which then gain energy, and so on.





Air molecule gets excited, gains energy, collides with another molecule and transfers energy to it 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.



50,000 B.C.: Gak Eisenberg invents the first and last silent mammoth whistle.

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 (below10 Hz).

Dear Doctor Science,
How come some of us can make armpit noises, and others can't?
-- Farley Upchurch, Mt. Vernon, Iowa

Dr. Science responds:
Armpit noise is made by a set of rudimentary vocal chords. Their range is limited to two tones: one a kind of flapping bass tone; the other a high-pitched whine resembling the noise made by a hungry mosquito. All of us possess these chords, but some are more practiced in

their use. I've met people who can produce a passable rendition of "The Star Spangled Banner," guaranteed to bring any party to an early close. Others of us have lost the use of these chords by using underarm deodorants, the leading cause of underarm laryngitis. If you want to "talk", you must live with odor. This is what science calls a no-win situation.

Dear Cecil:
Recently I read the useless fact that the quack of a duck will not echo. (1) Is this true? (I currently do not have access to either a duck or a canyon, or I would find out myself.) (2) Why not? (Assuming it is true.) (3) Are there other noises that will not echo? (4) Again, why not? --G. J. Thelin, Fresno, Dear California

Dear G.:
This is another example of faxlore--myths and factoids kept in circulation by people who obviously will believe anything. If you're ever organizing a poker game, you definitely want to invite these guys.

Personally, I recognized this claim immediately for what it was -- quackery. Preliminary inquiries confirmed this. Sure, there's such a thing as destructive interference, in which colliding waveforms cancel each other out. But how this would cause 100 percent attenuation of an echo 100 percent of the time in uncontrolled conditions was beyond even me.

But never mind my opinion. What we need here is science. Knowing the only way to settle the question for good was an experiment, I assigned Jane to assemble the apparatus and conduct a test. Here is her report:

> I spoke with several friends about the duck's quack question, even called the Michigan State University animal science department. No one could confirm or deny the claim, and no one at MSU seemed eager to stage a formal experiment, the wimps. I mentioned my dilemma to a visiting friend, and he said his wife, Shareen, had an in with the director of Mott Hashbarger Children's Farm and School in Flint. She had, on occasion, borrowed farm animals for events, and she was willing to get a duck and bring it down. After a quick phone call to the farm director, who gave his blessing, she obtained a duck and put it in a pet carrier.

But where to find a good echo? I live in mid-Michigan, after all. I called Glenn Brown, a sound engineer who has done work across the country. As luck would have it, Glenn remembered one place where, as a kid, he would go to produce great echoes. It's at the back of East Lansing High School--a sort of courtyard between two classroom wings, about 30 feet wide and 170 feet long. The hard surface of the buildings and perhaps a low hill opposite are highly conducive to reflecting sound.

So, with friends, duck, and camera in tow, we drove to ELHS. In the courtyard without the duck we easily produced some impressive echoes. Next we got the bird and sat down in the middle of the courtyard. We thought he would produce a big quack and the experiment would be over. No such luck. He just wouldn't quack. Probably he was nervous. Who wouldn't be? He was a sitting duck.

The three of us certainly quacked, though, such that we thought we might want to change the name of the experiment from 'does a duck's quack echo' to 'how to make three humans quack like a duck.' We tried to be inconspicuous, since school was in session and students could see us. However, a duck and three quacking humans is not the sort of scene that fades readily into the woodwork. The duck quacked in the cage, which was useless for our purposes, but when we took him out he was mute.

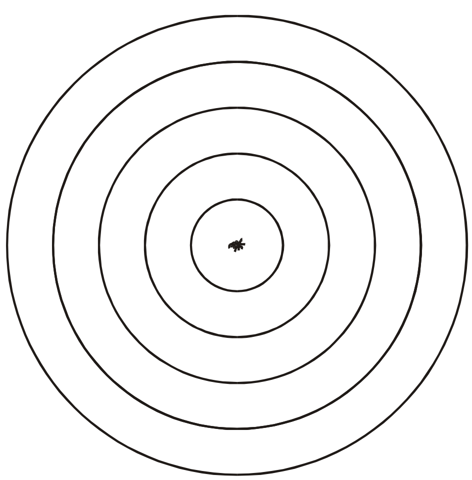
Finally Shareen had an inspiration. She held the duck by his body so that he could flap his wings, and ran up and down the length of the courtyard hoping to replicate the experience of flying. So much for being discreet. Incredibly enough, this wacky stratagem worked. The duck loved it and quacked like crazy for a minute. Yes, the quacks echoed. This was heard by the three of us and by an unidentified East Lansing High School teacher who came out to make sure we weren't engaging in duck torture. I was able to record the event but didn't get a good sound recording of the echo itself. But I do have a dandy clip of Shareen running up and down with the duck. I call it my 'duck tape.'

I wanted to reward my friends somehow, and offered to buy them lunch. They asked for roast duck. They're such comedians. They settled for soup and quackers.

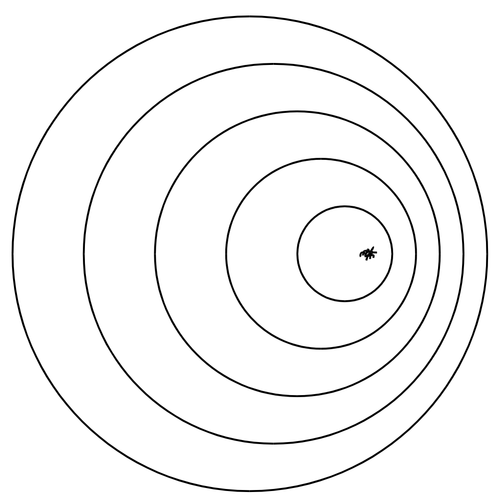
That Jane. What can I tell you? She quacks me up.

--CECIL ADAMS

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



Wave Pattern Created By A Stationary Bug wiggling its Legs in the Water



Wave Pattern Created By A Bug Swimming in Calm Water

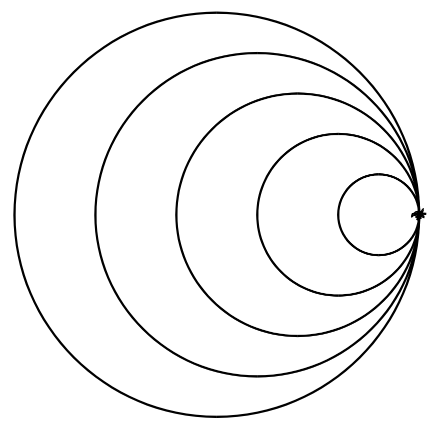
ripples on a pond (actually, they are ripples on a pond, ain't they? Curious, what?). The bug is unwittingly producing a traveling wave. It would look like this:
The waves spread out in all directions. The distance between the wave crests is the wavelength, λ. This wavelength is the same in all directions. 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***.

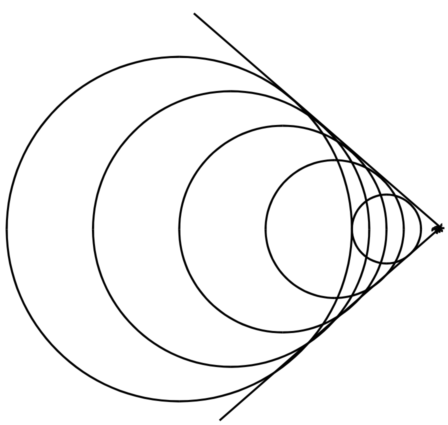
This happens because the bug makes a wave and then swims after it. So that, when he makes the next wave, it will start out closer to the first wave and so on. As the wave travels to the rear, it is already further away from the first wave, so the wavelength is longer and the frequency shorter. All the 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.



Wave Pattern Created By A Bug Swimming in Calm Water At the Speed of the Wave



Wave Pattern Created By A Bug Swimming in Calm Water Faster Than the Speed of the Wave

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:

$$v = f\lambda \qquad so \qquad f = \frac{v}{\lambda} \qquad and \qquad \lambda = \frac{v}{f}$$

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 $\boldsymbol{v_0}$ 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. The Physics Kahuna will patiently wait for you.

So ***λ'*** (wavelength collected by listener) is shorter than ***λ*** (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;

$$v = \frac{x}{t} \qquad x = v_s t$$

Since the time is the period we get:

$$x = v_s t \qquad = v_s T$$

The period and frequency are related by:

$$T = \frac{1}{f}$$

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

$$x = v_s T \qquad = v_s \left(\frac{1}{f} \right) \qquad x = \frac{v_s}{f}$$

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:

$$\lambda' = \lambda - \Delta\lambda \qquad \lambda' = \lambda - \frac{v_s}{f}$$

Because $\lambda = \frac{v}{f}$

We can write

$$\lambda' = \lambda - \frac{v_s}{f} \qquad \frac{v}{f'} = \frac{v}{f} - \frac{v_s}{f}$$

We can solve for ***f'***:

$$v = \left(\frac{v}{f} - \frac{v_s}{f} \right) f' \qquad vf = (v - v_s) f' \qquad \left(\frac{v}{(v - v_s)} \right) f = f'$$

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 $\boldsymbol{v_s}$ 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:

$$125 \frac{\cancel{km}}{\cancel{h}} \left(\frac{1\ \cancel{h}}{3\,600\ s} \right) \left(\frac{1\,000\ m}{1\ \cancel{km}} \right) = 34.72 \frac{m}{s}$$

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.

$$f' = f \left(\frac{v}{v - v_s} \right) = 550.0\ Hz \left(\frac{345 \frac{\cancel{m}}{\cancel{s}}}{345 \frac{\cancel{m}}{\cancel{s}} - 34.72 \frac{\cancel{m}}{\cancel{s}}} \right) = \boxed{612\ Hz}$$

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.

Disk vs Disc: A Public Radio Commentary by Bill Hammack

How you spell the word disk affects how you view laws about copying recordings of music and movies. Lying in the balance is billions of dollars, and perhaps the cultural legacy we'll pass on to our heirs.

Disk with a "k" came about in the mid-17th century, modeled on words like "whisk." Disc with a "c" arose a half-century later from the Latin discus. Most people used these two spellings interchangeably until late in the 19th century when they began using disc with a "c" to refer to phonograph records. This usage still persists in Compact Disc, spelled with a "c". Then in the 1940s, when engineers needed a term to describe the data storage devices of their computers they choose to spell disk with a "k." We still see this in the spelling of the "hard disk" of our computers.

Today, though, the distinction between these two spellings is no longer meaningful. In the past if you had a disc with a "c", like a phonograph record, there was no way it could become a part of your hard disk, spelled with a "k." If you had a record you could make a tape of it, but it was never as good as the original, and any copies of it were even worse. Now, of course, the digital revolution has erased the difference between the two spellings of disk. A computer can make a copy identical to the original.

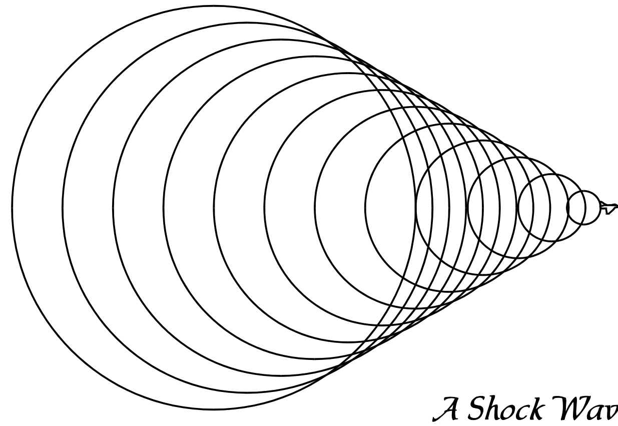
This, of course, has the entertainment industry terrified, especially when combined with the Internet, which provides unlimited distribution of these digital copies. Right now they're using software tricks to reduce copying - certain CDs now work only in players that can't make copies, but they know these software solutions are only temporary. Computer hackers always come up with ways to evade these measures. To counter this threat the industry is turning to Congress. They want intellectual property laws that make all copying illegal. We should be alarmed by these efforts.

We run the risk that every embodiment of thought or imagination may be subjected to some kind of commercial control. For example, as books become electronic, readers may lose the rights they've had since Gutenberg's time. The publishers of an electronic book can specify whether you can read the book all at once, or only in parts. And they can decide whether you read it once or a hundred times.

So, the risk is this: The literary and intellectual canon of the coming century may be locked into a digital vault accessible only to a few. As Congress writes laws to regulate digital intellectual property and copying, I think they should keep in mind an aphorism from T.S. Eliot. "Good poets borrow," he said, "great poets steal."

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.



A Shock Wave Created By A Supersonic Aircraft

Dear Doctor Science,
Why do telephone cords coil clockwise?
-- Joan Kozik from Cedar Rapids, IA

Dr. Science responds:
I could get away with saying that all telephone cords are manufactured in the northern hemisphere, but that would ignore the reality of 200 million Brazilian, Argentinean and Australian telephone cords. So, I'll tell you the real reason which is that voice transmissions only travel in a counterclockwise spiral. It has to do with the way the larynx attaches to the throat. Sonic vibrations are sent spinning from ligaments that connect clockwise and any attempt to re-direct this transmission induces phase cancellation. All you hear is a bored male voice telling you to hang up the phone and try your call later.

- The national sport of Japan is sumo wrestling.
- The only bone not broken so far during any ski accident is one located in the inner ear.
- The youngest American female to score an ace was Shirley Kunde in August 1943 at age 13.
- There are at least two sports in which the team has to move backwards to win-tug of war and rowing.
- Morihei Ueshiba, founder of Aikido, once pinned an opponent using only a single finger.
- Fossilized bird droppings are one of the chief exports of Nauru, an island nation in the Western Pacific.
- Honolulu is the only place in the United States that has a royal palace.
- If you leave Tokyo by plane at 7:00am, you will arrive in Honolulu at approximately 4:30pm the previous day.

December 8, 1941

(President Roosevelt's address to the Congress following the attack on Pearl Harbor on 7 December)

To the Congress of the United States:
Yesterday, Dec. 7, 1941 - a date which will live in infamy - the United States of America was suddenly and deliberately attacked by naval and air forces of the Empire of Japan. The United States was at peace with that nation and, at the solicitation of Japan, was still in conversation with the government and its emperor looking toward the maintenance of peace in the Pacific.

Indeed, one hour after Japanese air squadrons had commenced bombing in Oahu, the Japanese ambassador to the United States and his colleagues delivered to the Secretary of State a formal reply to a recent American message. While this reply stated that it seemed useless to continue the existing diplomatic negotiations, it contained no threat or hint of war or armed attack.

It will be recorded that the distance of Hawaii from Japan makes it obvious that the attack was deliberately planned many days or even weeks ago. During the intervening time, the Japanese government has deliberately sought to deceive the United States by false statements and expressions of hope for continued peace.

The attack yesterday on the Hawaiian Islands has caused severe damage to American naval and military forces. Very many American lives have been lost. In addition, American ships have been reported torpedoed on the high seas between San Francisco and Honolulu.

Yesterday, the Japanese government also launched an attack against Malaya.

Last night, Japanese forces attacked Hong Kong.

Last night, Japanese forces attacked Guam.

Last night, Japanese forces attacked the Philippine Islands.

Last night, the Japanese attacked Wake Island.

This morning, the Japanese attacked Midway Island.

Japan has, therefore, undertaken a surprise offensive extending throughout the Pacific area. The facts of yesterday speak for themselves. The people of the United States have already formed their opinions and well understand the implications to the very life and safety of our nation.

As commander in chief of the Army and Navy, I have directed that all measures be taken for our defense.

Always will we remember the character of the onslaught against us.

No matter how long it may take us to overcome this premeditated invasion, the American people in their righteous might will win through to absolute victory.
I believe I interpret the will of the Congress and of the people when I assert that we will not only defend ourselves to the uttermost, but will make very certain that this form of treachery shall never endanger us again.

Hostilities exist. There is no blinking at the fact that that our people, our territory and our interests are in grave danger.

With confidence in our armed forces - with the unbounding determination of our people - we will gain the inevitable triumph - so help us God.

I ask that the Congress declare that since the unprovoked and dastardly attack by Japan on Sunday, Dec. 7, a state of war has existed between the United States and the Japanese Empire.

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 Physics Kahuna 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 Physics Kahuna 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. The Physics Kahuna himself cannot tell the difference.

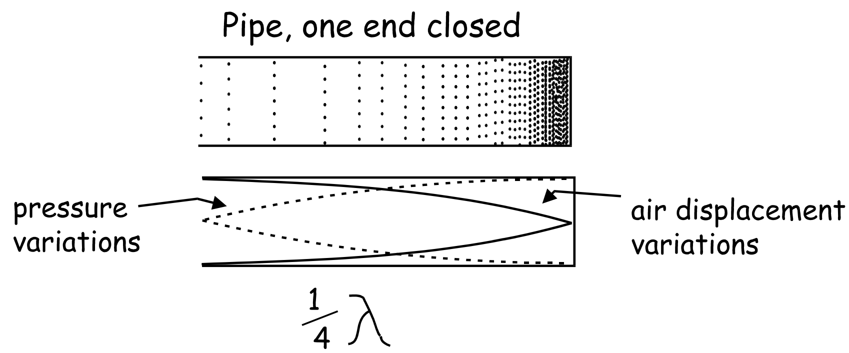
Resonance Discussed: Resonance is sometimes called ***sympathetic vibration***. It means to "re sound" or "sound again". If two objects which have the same natural frequency are placed near each other, and one is set to vibrate, the other one will begin to vibrate as well.

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.

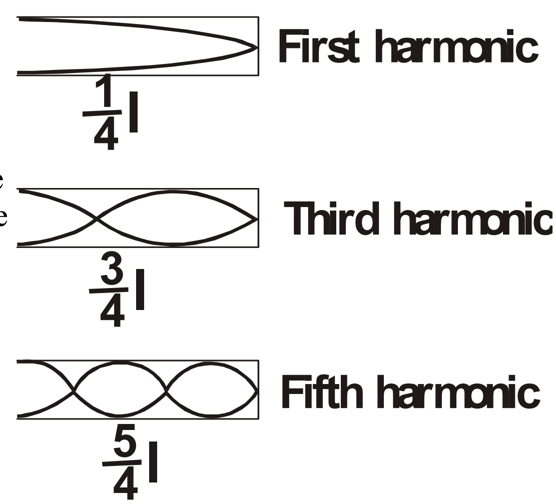
A common demonstration of resonance can be done with a book. The book is hung from a bar. A person applies a puff of air to the book, causing it to swing a little. When it comes all the way back from the swing, another puff is applied. It swings just a bit farther out. Apply yet another puff, it swings 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, 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 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 ¾ of the pipe's length, then 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:

$$v = f\lambda \quad = f(4l) \qquad f = \frac{v}{4l}$$

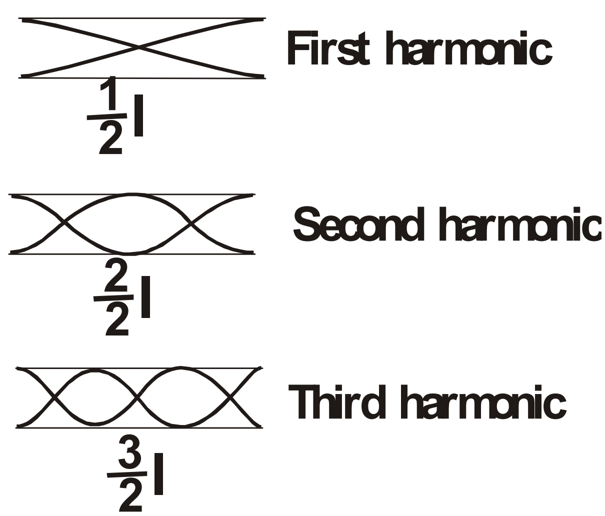
If we want the frequency of the third or fifth or whatever harmonic, we would get:

$$f_n = n\frac{v}{4L} \qquad n = 1, 3, 5, \ldots$$

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:

$$\lambda_n = \frac{4l}{n} \qquad n = 1, 3, 5, \ldots$$



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.

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

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):

$$f_n = n\frac{v}{4L} \qquad f_1 = \frac{v}{4L}$$

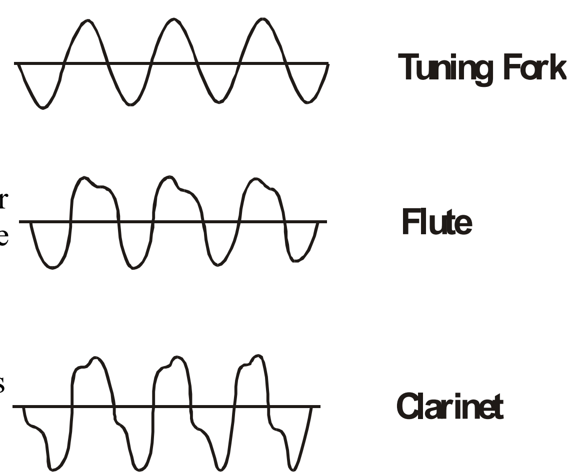
$$f_1 = 345\frac{\cancel{m}}{s}\left(\frac{1}{4[1.50\ \cancel{m}]}\right) = \boxed{57.5\ Hz}$$

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

$$f_3 = n(f_1) = 3(57.5\ Hz) = \boxed{172\ Hz}$$

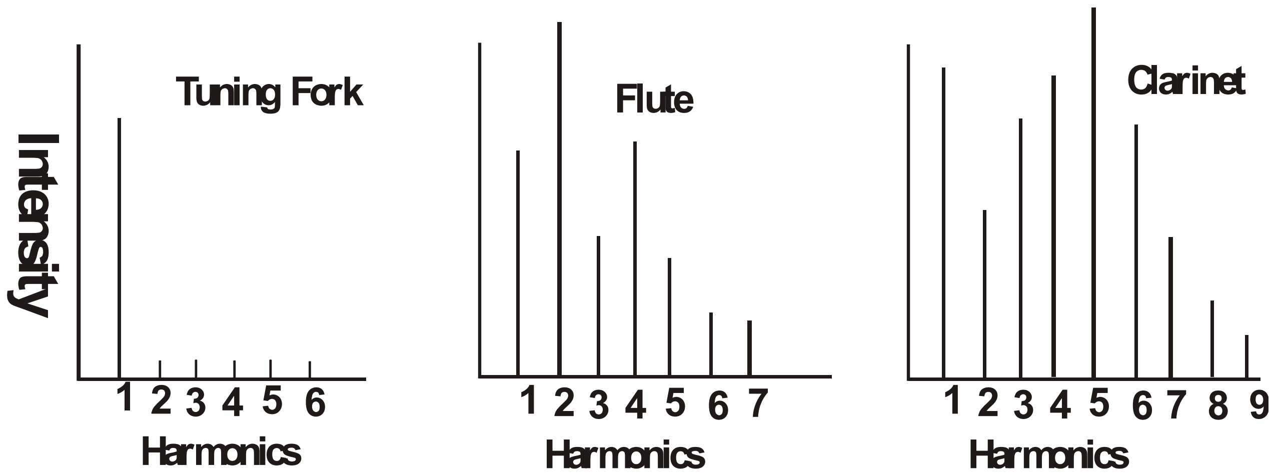
$$f_5 = n(f_1) = 5(57.5\ Hz) = \boxed{288\ Hz}$$

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.

Dear Doctor Science,
If you can hear the ocean in a seashell, why is it that you can't hear the forest in a pinecone?
-- Enrico Uva from Montreal, Quebec

Dr Science responds:
You used to be able to, but now all pinecones are treated with sound-damping toxic waste to ensure that they don't harbor the pernicious ear-boring fir beetle. This creature can scuttle out of a pine cone and into your ear faster than you can say "Paul Bunyan." Once inside, it quickly bores into the center of your brain, where it lays its eggs. When they hatch, they feed on the choice parts of your cerebellum, leaving you fit only for life as a community college administrator. Better content yourself with the harmless seashell.

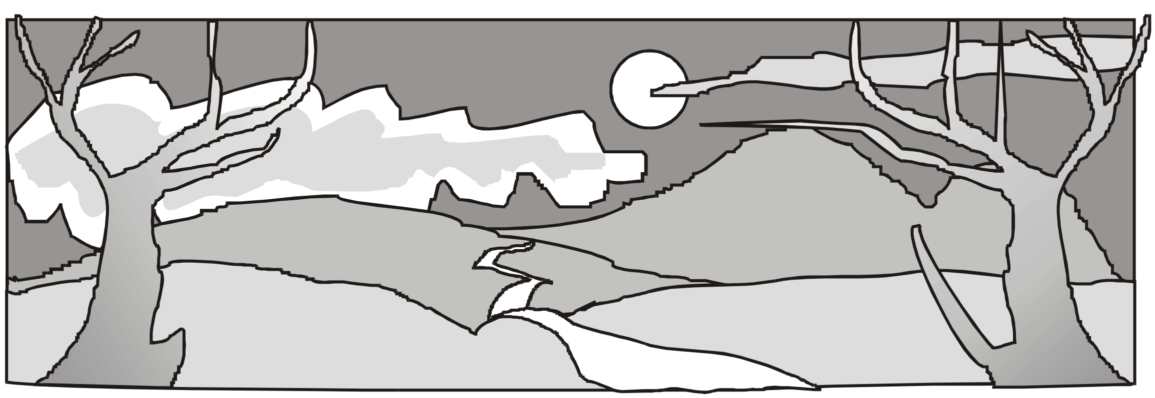
The Highwayman (continued)

He turned; he spurred to the West; he did not know she stood
Bowed with her head o'er the musket, drenched with her own red blood!
Not till the dawn he heard it; his face grew grey to hear
How Bess the landlord's daughter,
The landlord's black-eyed daughter,
Had watched for her love in the moonlight, and died in the darkness there.

Back he spurred like a madman, shrieking a curse to the sky,
With the white road smoking behind him and his rapier brandished high!
Blood-red were his spurs i' the golden noon; wine red was his velvet coat,
When they shot him down on the highway,
Down like a dog on the highway,
And he lay in his blood on the highway, with a bunch of lace at his throat.

And still of a winter's night, they say, when the wind is in the trees,
When the moon is a ghostly galleon tossed upon cloudy seas,
When the road is a ribbon of moonlight over the purple moor,
A highwayman comes riding,
Riding, riding,
A highwayman comes riding, up to the old inn-door.

Over the cobbles he clatters and clangs in the dark inn yard.
And he taps with his whip on the shutters, but all is locked and barred;
He whistles a tune to the window, and who should be waiting there
But the landlord's black-eyed daughter,
Bess, the landlord's daughter,
Plaiting a dark red love-knot into her long black hair.



Dear Cecil:
How did they mass-produce those old-fashioned cylinder records? A conventional molding press, like they use for discs, would leave some sort of line where the two halves met, which would show up as a click or thump when the cylinder was played. How did they make 3-D moldings of such accuracy in the 1890s? Or did the artistes just make the same recording over and over again? --Winfield S., Chicago
Dear Winfield:

They sure did, at least at the beginning. This is why you didn't see a lot of albums selling 18 million copies in 1887. The need for a cheap and easy method of reproduction was one of the first problems the early recording industry faced, and the problem you describe was one of the reasons why cylinders lost out to discs as the principal recording medium.

In the very beginning, of course, a little thing like a seam on the recording surface didn't matter too much. On Edison's original phonograph, the ends of the tinfoil sheet that recorded the sound were just tucked into a slot that ran the length of the metal cylinder that the foil was wrapped around. You did get a click this way, but since you also got an indescribable barrage of burps, wheezes, and rasps, the first recording devices being a little on the rustic side, it seems probable that you did not object to the clicks so much. Later, the recording blanks were made of wax, which could be cast in one piece, eliminating the click, if nothing else.

When records first began to be sold commercially, the only way to make additional copies was to have the artistes make the same recording over and over. You would hire, say, a brass band, which you would surround with a phalanx of recording machines loaded with blank discs, and you'd get some guy with a suitably stentorian voice to go around to each machine, flip it on for a second, and holler the title of the piece into the speaking horn. Then you'd turn on all the machines at once, and the band would play as much of any given tune as would conveniently fit onto the cylinders, which was generally about two minutes' worth. Then you changed cylinders and started over. Apart from being stupefyingly monotonous for the performers, this method was very slow.

Eventually somebody hit on the idea of recording additional cylinders off a master cylinder by means of a pantograph, which was an arrangement of levers and wires that transmitted the sound vibrations from the stylus on the master disc to that on the receiving disc. This was faster and less boring, but the masters tended to wear out quickly, and then the band had to go at it again.

Finally, around the turn of the century, Edison's phonograph company developed a reliable method for mass production. They coated the wax master with a thin layer of gold by an electrical process, coated the gold layer with a copper layer for strength, then melted out the original wax. This left a negative metal mold. Then they put a wax blank inside and applied heat and pressure. When the wax cooled, it shrank a little. In addition, the master and blank were tapered slightly--one end was slightly wider than the other. The combination of shrinkage and taper was enough to let them slip the master off the copy without (a) damaging it or (b) leaving a seam.

Actually, this method had occurred to Edison and his buddies fairly early on, but the first recording styli gouged out such deep grooves that the shrinkage wasn't enough to enable them to clear. The development of the sapphire-tip stylus, which made shallower indentations, cleared up this problem. Unfortunately, by the time they got all this worked out, cylinders were beginning to decline in favor of discs, which were longer playing, among other things. So it was all for nothing, as is often the case in the record business.

--CECIL ADAMS

Dear Cecil:
I have observed that traveling high speeds causes strange things to occur (e.g., the Charger's hubcaps in Bullitt regenerated twice during the high speed chase scene). If I traveled down Austin Avenue at a speed exceeding Mach 1 (the speed of sound) would the noises made by the people on the streets be distorted or totally inaudible to me? While cruising at this speed, if I blasted my car radio, would the people on the streets hear it as I would, or would I be traveling faster than radio waves, causing my radio to die? What phenomenon would occur if I shifted into second around North Avenue and my Buick exceeded the speed of light? This information will be helpful when I rush my wife to the hospital sometime in January to deliver our baby.
--Life in the Fast Lane, Chicago

Dear Life:
Nice to hear from a guy who takes a practical view of things. Dealing with the easy parts of your question first: At the speed of sound you won't hear sounds happening behind you, because the sound waves won't be able to catch up with you. You'll hear sounds occurring in front of you, but they'll be increased in pitch about an octave due to the Doppler effect--i.e., as you move toward a sound source, you crowd up on the oncoming sound waves, which increases their frequency relative to you. By the same token, people on the street won't hear you coming, but they'll hear you (and a sonic boom) after you've passed--with the pitch decreased about an octave.

What was more interesting to the Straight Dope Science Advisory Board was what you would hear if you turned on your car radio at the speed of sound. If you keep the windows closed there's no problem, because you, the radio, and the air will all be stationary relative to one another. With the windows open, however, you wouldn't hear the rear deck speakers at all--the air carrying the sound waves would be blown backward too quickly. However, you'd hear the dashboard speaker normally (or as normally as you'd hear anything at 700 MPH)--the twin Doppler effects of source to air and air to observer would cancel out.

Finally, regarding your last question, don't you know the velocity of light is the speed limit of the universe? Any attempt to exceed it would defy one of the fundamental principles of creation. Besides, it's hell on the tires.

--CECIL ADAMS

Dear Cecil:
Can operatic sopranos really break glasses with their high notes? What note does the trick? How come they don't break windows and eyeglasses and whatnot at the same time? Can women do this better than men? Can I learn how? Or have I been the victim of an elaborate hoax? --Vox Clamantis, Chicago

Dear Vox:
I dunno--you ever buy whole-life insurance? Now _there_ was a hoax. Shattering glasses, on the other hand, is entirely legit. Enrico Caruso and Italian opera singer Beniamino Gigli are said to have managed it, and I seem to remember Ella Fitzgerald doing it once in a Memorex commercial.

The technique is simple. First you find somebody with perfect pitch and leather lungs. Then get a crystal glass and tap it with a spoon to determine its natural frequency of vibration (this varies with the glass). Next have the singer let loose with precisely the same note. When he or she is dead-on pitchwise, the glass will commence to resonate, i.e., vibrate. Then turn up the V. Bingo, instant ground glass.

What we have here is a graphic demonstration of forced oscillation resonance. If something has a natural rate of vibration, pump in more energy of the same rate and with luck the thing will vibrate so bad it'll self-destruct. It's like giving somebody on a swing a good shove at the top of every arc--soon they'll reach escape velocity and soon after that they'll be picking vertebrae out of their sinuses.

Breaking glasses, however, is strictly light entertainment. For real forced oscillation action you want a suspension bridge. In 1831 troops crossing a suspension bridge near Manchester, England, supposedly marched in time to the bridge's sway. Boy, did they get a surprise. Ever since soldiers have been told to break step when crossing bridges. The same fate befell the Tacoma Narrows suspension bridge in Washington State on November 7, 1940, only it wasn't soldiers that caused it to collapse, it was the wind.

But back to the home front. Crystal is more vulnerable than ordinary glass because it has more internal structure, which allows waves to propagate. (Take my word for it.) But you can annihilate damn near anything given enough volume. One physicist, obviously one of your classic Roommates From Hell, claims he inadvertently shattered a glass lamp shade while playing the clarinet.

Think of the possibilities. Most of us don't have the pipes to break glasses by sheer voice power, but we all have clarinets, don't we? Unfortunately, none of the standard physics cookbooks gives a detailed glass-bustin' recipe. Too bad. A fascinating classroom demonstration like this would surely convince many young people to give up MTV and devote their lives to science.

SHATTERING MYTHS

Dear Cecil:
In the matter of glass-shattering vocalism, Cecil seems to have been led astray by Gunter Grass's fictional tin drummer, Oskar. In fact, there is no authentic record of glass being broken by the unamplified human voice. Dorothy Caruso categorically denied rumors that

her late husband had accomplished the feat; a fortiori it was beyond Gigli's comparatively feeble instrument. Practically speaking, there are reasons to believe the thing impossible, and without going into technical detail, the following are among them:

(1) **Glass is simply much too strong. Try shattering a wine glass in your (gloved) fingers. Not easy. Now imagine doing the same with the puny little bands of your vocal cords.**
(2) **(2) Coupling acoustic energy from larynx-to-air-to-glass is highly inefficient due to large impedance mismatches; by contrast, marching troops couple very efficiently to bridge platforms.**
(3) **(3) In glass shattering attempts, resonance or no resonance, the glass structure finds other ways to dissipate energy short of fracturing.**

Remember the playground swing in which successive small but well-timed swings sent your sister sailing higher and higher? And the tales of going "over the top" when the process went critical? Alas! it never happened, because other dynamic processes supervened ("Gee, Mom, we were just playing") before the longed-for loop could occur.

--Timon, Dallas

Dear Timon:
A fortiori? Supervened? Boy, I see I wasn't the only one to get a Word-A-Day calendar for Christmas. As for glasses, let's clarify one thing: it is certainly possible to shatter glasses with the amplified human voice. The folks at the Memtek company in Fort Worth, Texas, which makes Memorex recording tape, do it all the time for sales demonstrations and whatnot. (You'll remember that Memorex used to run those TV commercials showing Ella Fitzgerald and others breaking glasses with their voices.)

What's more, they do it pretty much the way I described: they go out and get a drinking glass with high lead content, tunk it with a rubber mallet to make it ring, then read the frequency on an analyzer. Then they get a singer to sing the same note (typically F above middle C), amplify it to maybe 92, 94 decibels, and with luck you get glass shrapnellini. Memorex technicians using a strobe have found that prior to the break the sound causes the rim of the glass to deflect as much as a quarter inch. (I get this from Rick Needham, engineering manager, lest you think I am making this up.)

Your beef is that I suggested this could be done with the unamplified human voice. I'll grant I haven't been able to turn up a documented instance of this, but it seems subsidiary to my main point, which is that you can shatter glasses with sound, and furthermore that the human voice, which can generate a relatively pure tone, is well suited to this purpose. Furthermore, none of the technical people I spoke to about this seemed to think doing it by voice alone was completely impossible. Admittedly 90-plus decibels is pretty damn loud, but one of the reasons the Memtek folks crank it up that much is that they're using an inexpensive ($7) glass rather than fine crystal, which is more fragile. So let's not be so negative, Timsy. It's the can-do attitude that has made this country great.

BRIDGE CRASH NEWS FLASH!

In his recent treatise on whether singers can break glasses with their voices, Cecil mentioned "forced oscillation resonance," in which an external force amplifies the natural vibration of an object, sometimes with destructive results. As an example he cited the 1940 collapse of the Tacoma Narrows bridge. The usual explanation for this disaster is that the wind gusted (to be precise, "generated a train of vortices") in perfect synch with the bridge's natural rate of bounce, causing its demise.

Reader Wilbur Pan has alerted us to a recent report in Science News heaping abuse on this widely held view. Mathematicians Joseph McKenna and Alan Lazer doubt that a storm could produce the perfectly timed winds required. They're working on a "non-linear" model of bridge behavior they hope will provide a better explanation. The main problem apparently is that when the roadway of a lightly constructed suspension bridge flexes, the cables supporting it go slack, introducing an element of unpredictability in which little causes (i.e., the wind) produce big results (i.e., a collapsing bridge). They hope to have the mathematical model describing this effect finished in five years--not the most aggressive schedule in the world, but apparently this is government work. You'll read about it here first.

--CECIL ADAMS

Dear Doctor Science,
Is there a gene missing in men's ear canals that gives them selective hearing?
-- Sue Neff from Missoula, MT

Yes, you could say that. That particular gene resides on the Ear, Nose and Throat Chromosome and also suppresses emotive speech. When a man suspects that a woman wants to talk about their relationship, this gene literally takes over the autonomic nervous system, causing rapid, shallow breathing, a drop in blood pressure, and an intense desire to watch sports on television. Biogenetic engineering hopes to create a new "feminist" male, whose genetic makeup will more closely mirror what women want men to be. So far the only working prototype is celebrity John Davidson and, based on this data, the FDA is considering banning experimentation on living organisms.