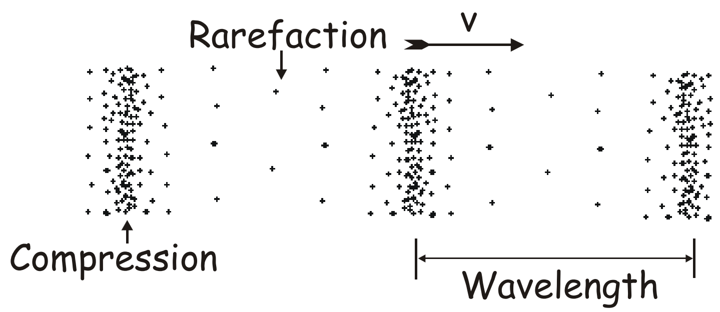
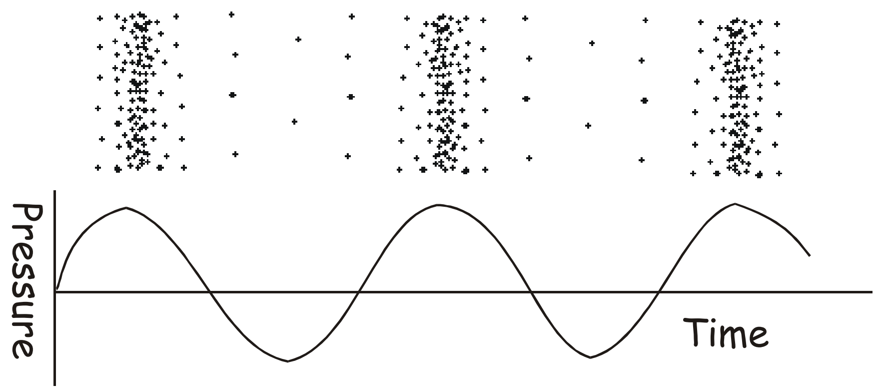
AP Physics – Doppler Effect

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. This is because our ears are set up for listening to sounds that move
through the atmosphere.

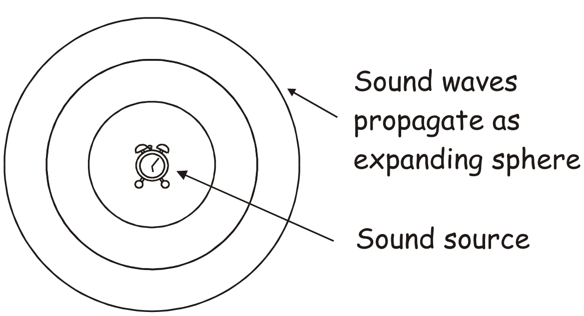


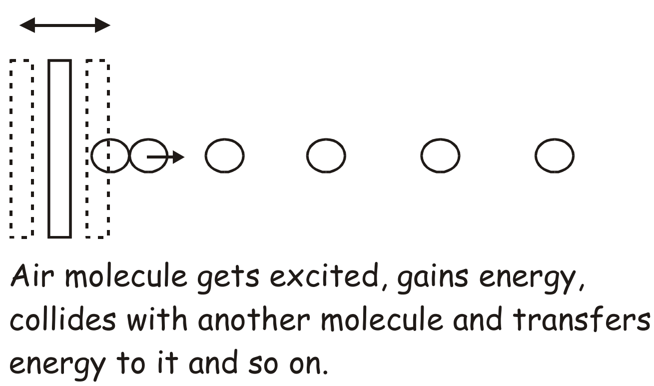
The disturbance which travels through air is the compression of air molecules – they are squeezed together and pulled apart. Sound is a series of traveling high pressure and low pressure fronts.

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, don't be confused between the actual wave and a visual representation of it on a graph.



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.

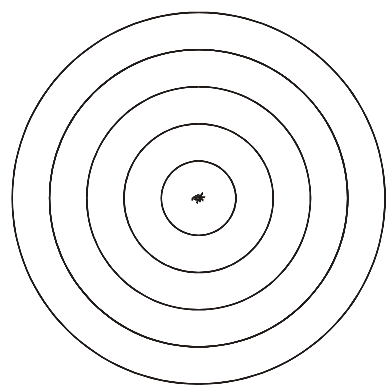
Audible Spectrum: The human ear is not the world's best sound receptor, although it does all right (if you take care of them). A typical person can hear sounds whose frequency ranges from 20 Hz to about 20 000 Hz. This is known as the ***audio spectrum***. Sounds with a higher frequency are called ***ultrasonic*** 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 (below10 Hz).

** Memorize for multiple choice – Sound travels faster in solids and the slowest in gasses. Sound also travels faster as the temperature of the medium (solid, liquid, gas) increases.

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. The bug is unwittingly producing a traveling wave.

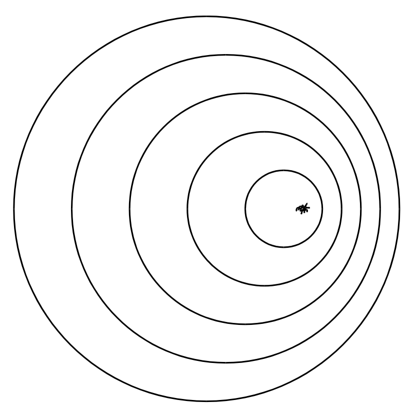
The waves spread out in all directions. The distance between the wave crests is the wavelength, λ. This wavelength is the same in all directions.



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

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***.

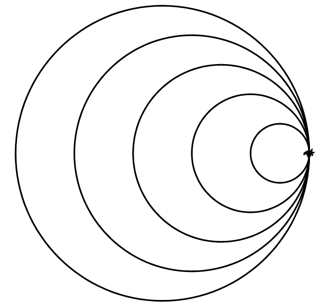


Wave Pattern Created By A Bug Swimming in Calm Water

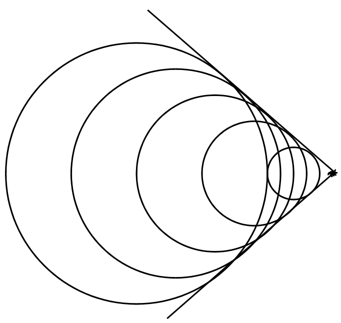
This happens because the bug makes a wave and then swims after it. So that, when he makes the next wave, it will start out closer to the first wave and so on. As the wave travels to the rear, it is already further away from the first wave, so the wavelength is longer and the frequency shorter. All the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

$$f_o = f_s \left(\frac{v + v_o}{v - v_s} \right)$$

- Use positive values of v_o and v_s if the motion is toward
  - ⇨ Frequency appears higher
- Use negative values of v_o and v_s if the motion is away
  - ⇨ Frequency appears lower

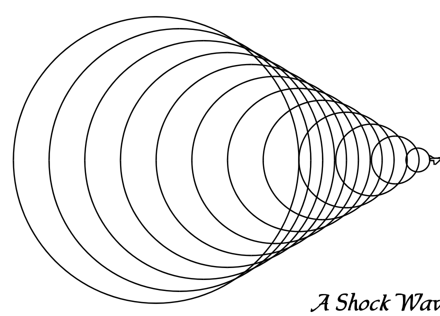
f_0 = observed frequency **f_s = frequency of source** **v = velocity of wave**
v_o = velocity of observer **v_s = velocity of source**

Example Problems:

1) A train is traveling at 35 m/s & it has a 550.0 Hz train whistle. Assume the speed of sound is 345 m/s. What is frequency heard by a stationary listener (a) as the train approaches and (b) as the train leaves the station?

2) An ambulance travels down a highway at a speed of 75 mi/h (1mph = 0.447 m/s), its siren emitting sound at a frequency of 400 Hz. What frequency is heard by a passenger in a car traveling at 55 mi/h in the opposite direction as the ambulance? What frequency is heard after they pass each other and are moving away from each other? (vs = 345 m/s)

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.



A Shock Wave Created By A Supersonic Aircraft

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.