Music and Sound Waves

The propagation of sound waves is fascinating. My goal is to describe these waves clearly and accurately, without equations. A rigorous mathematical description is presented in another section. Some technical jargon is hard to avoid; double clicking on most blue-highlighted words or symbols will directly access a Glossary. Hopefully the graphics and animations available via the web add spice to the description. Blue highlighted words that lead to images, etc. are followed by the size of the file in kilobytes (kb).

Air

Music travels through air as sound waves. I am sitting in my music room, which is 19 feet long, 14 feet wide and 8 feet high. At the moment it is dead silent, but in fact a lot of action is taking place. The room contains a huge number of air molecules (about $1.6x10^{27}$; see scientific notation) that collectively weigh 160 pounds. Air is actually fairly substantial stuff. But there is still a lot of empty space between the molecules in the room, as shown by a simulated microscopic snapshot of air molecules (5.5 kb) in a cube about 1/2 of one-millionth of an inch wide. For easier visibility the size of the dots is exaggerated by a factor of roughly 2-1/2 compared to true scale. The diameter of a human hair is about 6000 times larger than the cube.

78% of the air molecules are nitrogen, and almost all of the rest are oxygen. Both molecules are shaped like tiny dumbbells. The molecules are moving in random directions at an average speed of over 1000 miles per hour. Each molecule has about 5 billion collisions per second - on average one collision occurs after traveling 7 times the width of the cube in the snapshot. The little dumbbells are also spinning frantically. (Julio Geo-Banacloch has created a Java applet that illustrates collisions of monatomic molecules). The total kinetic energy in the air molecules in the room is astounding - more than the kinetic energy of seven 4,800-lb Mercedes hurtling along at 100 MPH! This is difficult to comprehend in this dead-quiet room.

The molecules are furiously colliding with my eardrums, exerting a pressure of over one ton per square foot. But the collisions on one side of my eardrum are precisely balanced by collisions on the other side; my eardrums don't move, and I hear nothing. (The eustachian tube equalizes the pressure on either side of the eardrum as long as pressure varies slowly, such as for changes in barometric pressure). Sound is typically described as a small rapid variation in pressure. This is one part of the story, but there is another effect, a variation of the average molecular velocity, which is an essential part of the propagation of a sound wave.

Sound

Today my music room is also a sound laboratory. A 400 Hz test tone is now being played by my sound system (play the tone - 12 kb wav file; this doesn't work on all computers). The motion of the air molecules is no longer totally random. There are three changes:

- there are bands about 3-feet apart where the molecules are slightly bunched up, separated by bands where the molecules are slightly thinned out.
- the temperature is higher in the bunched up bands (temperature is a measure of the average kinetic energy per molecule). This, plus the first change, represents a pressure variation.
- the average velocity of the molecules in the bunched up bands causes a net drift of molecules towards me; in the thinned out bands there is a net drift away from me. This is the velocity variation that is usually ignored in the description of a sound wave.

The ensemble of these bands is moving towards me at 770 MPH, the speed of sound. This is your basic sound wave. (Here I am lying a little. My real room is full of reflections from walls and the ceiling which complicate things greatly. To keep things reasonable, I am describing a wave propagating in an unbounded volume).

It is at first hard to understand that the wave traveling towards me at 770 MPH does not mean the molecules are traveling towards me at 770 MPH. If you stretch out a garden hose straight for about 20 feet and rapidly shake one end back and forth a snaky wave will travel away from you down the hose. The hose isn't going anywhere, but the wave is. This is illustrated by a snaky wave video clip (41 kb). The small circles are attached at fixed points at the center and ends of the "hose;" as the wave moves to the right, the circles move up and down, but not much to the left or right. All types of waves (hose, sound, water, electromagnetic, football fans, etc.) have a lot in common mathematically. In this sense the peaks and valleys of the hose in the video are analogous to the bands of molecules that are bunched up and depleted, respectively. However the underlying physical processes for a hose wave and a sound wave are completely different.

A cartoon video of molecules in a sound wave illustrates the way a sound wave propagates (197 kb - This one takes patience; the full file has to load and be digested before the real animation begins. If you don't see concentrated bands of molecules moving to the right, it isn't doing its thing). Both the bunching up of the molecules and the average molecular velocity are greatly exaggerated in order to be visible. The speed of the wave is obviously also greatly reduced. Note how the molecules in the bunched up region are drifting to the right, and molecules in the depleted region are drifting to the left. (See a similar animation , and animations of other wave phenomena, created by Dan Russell at Kettering University. Also takes patience).

Compared to the action taking place when the room was silent, the true changes in molecular motion are minuscule. For a very loud sound volume, a sound pressure level (SPL) of 117 dB, which is about as loud as any rock concert gets, the bunched-up bands have an extra 140 molecules for every million molecules. Bands in-between have 140 fewer. The temperature increase is 0.03 ^{0}F. The peak average molecular velocity is about 0.1 MPH, first towards me, and then away from me.

Visualize a 1-foot diameter balloon floating in the middle of the room. The bunching up of molecules, and the temperature increase, that correspond to an increase in pressure, cause the balloon diameter to shrink by 0.0006 inches - roughly 1/5 the thickness of a human hair. It then swells by an equal amount as the thinned out band passes by. The average molecular velocity causes the balloon to sway back and forth by 0.00076 inches. The maximum pressure change due to the sound is small compared to the ton per square foot in the silent room, but is still a very noticeable 0.4 lbs. per square foot for the 117 dB level. The key difference between silence and sound is that the sound pressure outside my ear is not balanced by an equal pressure inside my ear, so my eardrums move back and forth 400 times per second. The same pressure imbalance exists for my chest cavity, where this level of sound can easily be felt (at lower frequencies anyway).

If the frequency is halved, making the tone one octave lower, the distance between the bands of molecules is doubled and the balloon moves back and forth twice as far. The 0.03 ^{0}F temperature variation, 141 per million variation in molecular density, and 0.1 MPH velocity variation remain the same.

The pressure and average molecular velocity are both essential characteristics of a sound wave. The human ear does respond to both pressure and velocity, but for much of the audio spectrum the response to pressure is the dominant factor as shown in the physics section.

Velocity and speed are used here in describing quite different characteristics, and this certainly can be confusing. To sum up, the contexts are:

1. The random motion of the molecules: molecules going in all directions, at an average speed of over 1000 miles per hour. This chaotic action takes place with or without a sound wave.
2. The average molecular velocity, which causes bands of molecules to drift back and forth, at a peak velocity of 0.1 miles per hour for a 117 dB sound level. This velocity is added on top of the random motion, and causes a systematic movement of the molecules. For a wave traveling from left to right, as viewed from a stationary point, this velocity is at one moment to the left, and then to the right, reversing direction at the frequency of the sound wave. Looking at the entire wave at one instant in time, there are bands where the velocity is to the left, alternating with bands where it is towards the right.
3. The velocity of the wave itself, 770 miles per hour. This is the apparent motion of the wave contour, or any feature, such as the wave crest. For a wave traveling from left to right, this velocity is purely to the right, and it is uniform throughout the entire wave. This is probably the most difficult velocity to understand, and I think the video clips given above are a better description than any words I can think of.

The average molecular velocity of a sound wave is much smaller than typical wind velocities. Why don't we hear the wind as a sound of ear-shattering volume? You can find my hypothesis here.

Wave direction

What is the difference between a sound wave traveling towards the left or traveling towards the right? A stationary observer sees exactly the same pressure variation for a wave in either direction. But for a wave traveling to the right the molecules in the bunched up bands drift towards the right, and the molecules in the thinned bands drift to the left. Room reflections, ignored prior to this point, create standing waves, which don't travel anywhere. In a standing wave the pressure (i.e. temperature and molecular density) also varies exactly like a wave moving to the left or to the right. The difference in this case is that at a line smack in the middle of band where the molecules are bunched up the average molecular velocity is zero. A little to the right of this line the average velocity is towards one direction, and a little to the left of the line the average velocity is towards the opposite direction. Standing waves occur in a room mainly at frequencies below 100 Hz, and are responsible for room resonances, which are discussed ad nauseam in the section on room acoustics.

There is no flow of sound energy in a standing wave. For a wave traveling right or left, there is power flow in the direction of wave travel. Average molecular velocity and pressure are multiplied together to produce the power flow, which is 1 Watt per square meter (peak) for the 117 dB SPL sound level. For a sound wave there is no net flow of molecules. There would be a net flow if the average velocity in the bunched-up region was equal in magnitude to the velocity in the opposite direction in the thinned region. However as shown in another section, there is a uniform velocity component which just cancels out any net molecular flow. So on average the molecules just oscillate back and forth around a fixed position. Even though there is no mass flow, sound waves, like light waves, do carry momentum. (see plane waves in the physics section)

Music

Music is a conglomerate of sound waves at different frequencies. The molecules in the room no longer align in simple bands, but form a complex and ever-changing pattern - like the surface of the ocean, but in 3-D. About the only thing that stays the same as for the 400 Hz tone is that the whole wave pattern still travels as a unit at 770 MPH.

Physics (or at least my knowledge thereof) doesn't have a lot more to add beyond this point. But physiology, and psychoacoustics, have quite a bit to say about music and sound. This is the subject of the next section, which can be found by clicking on music and the human ear Another source of information on sound is the acoustics FAQ page maintained by Campanella Assiciates. Joe Wolfe has created an excellent site on the acoustics of musical instruments and related topics.

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