Physics and Math of Music — Day 2 — The ear

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Many oscillators resonating

When you shake one pendulum back and forth at its natural frequency, it resonates. Now, what happens when you shake more than one pendulum at the same time? The ones that have a natural frequency that matches the shaking will start swinging; the other ones won't. So, if we have pendulums of *many* different frequencies, we can identify the frequency of shaking just by checking which pendulums are moving. That's how your ear works!

A model of the ear

The ear detects the frequency of sound by using thousands of little oscillators. Figure 1 shows how this works:

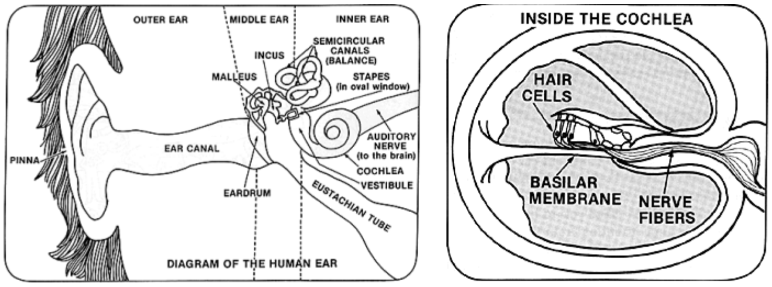

Figure 1: On the left is a view of the inside of your ear. On the right is a cross-section of the cochlea, where sound is detected by tiny hair cells — resonating oscillators! Thanks to `http://clerccenter.gallaudet.edu/InfoToGo/535/535-1.html` for the nice ear pictures.

Each one of those little hair cells is an oscillator, just like one of our pendulums. The force that shakes them comes in from the air: if a hair has a natural frequency matching a sound in the air, it starts vibrating.

Multiple frequencies at the same time

A sound is made up of many different frequencies, and our ears allow us to hear them all. Once you know all of the frequencies in a sound[1], you know everything about the sound. This measurement of the frequencies that make up a wave is called a *Fourier transform.* It is so useful to look at the frequencies of a wave that the Fourier transform is used for everything; from encoding your `mp3`s and cleaning up musical recordings to matching up fingerprints for the FBI.

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[1] To perfectly recreate the sound, you would also need the *phases* of all of the frequencies — something a microphone can measure but our ears can't.

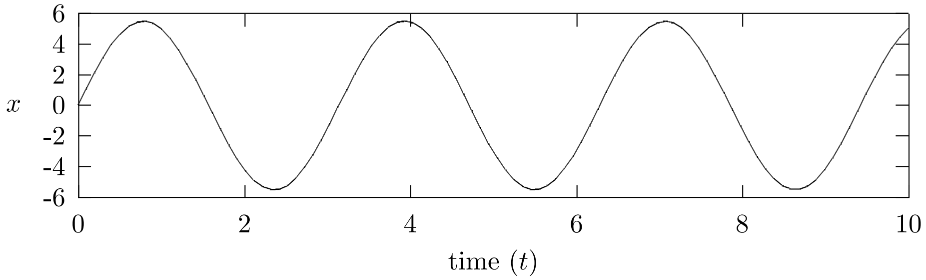

Figure 2: Plot of a simple sine wave: $x = A\sin(2\pi ft)$.

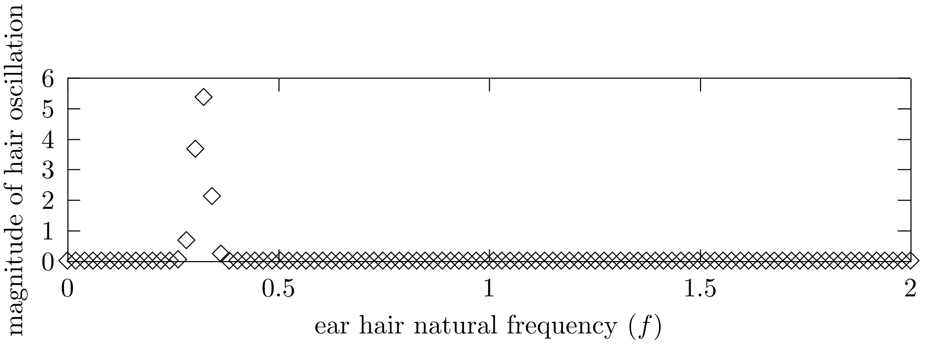

Figure 3: The response of your ear to a simple sine wave — just a few hairs oscillate.

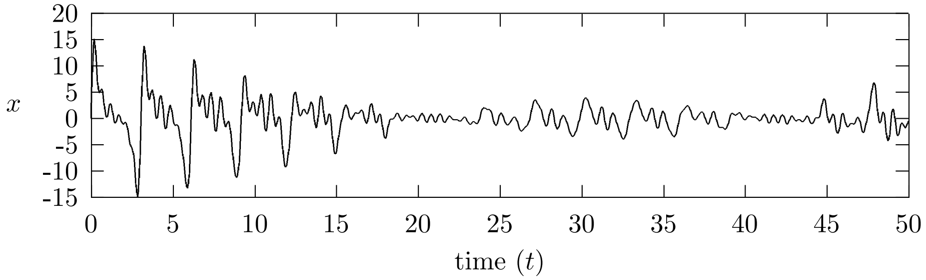

Figure 4: Plot of more complicated wave: the sound of a note on a piano.

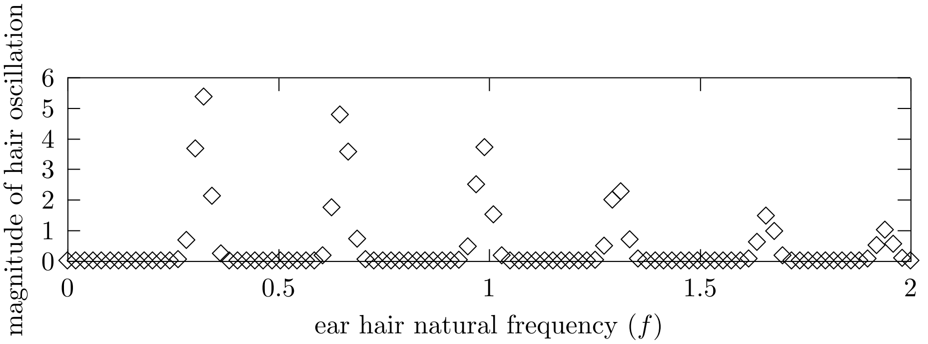

Figure 5: The response of your ear to a piano note — many different hairs oscillate. Their oscillations will also change over time as the note decays.