Tu. 3/12: Ch 6 *The Human Ear* **Th. 3/14:** Ch 17 *The Ear Revisited &* http://dx.doi.org/10.1063/1.3603917 http://phys.org/news/2013-02-human-fourier-uncertainty-principle.html	HW8: Ch6: 2,4^{W}… Ch17: 1,3,4,16,20,23	**Mon. 3/11** or **Tues. 3/12:** Lab 9 *Electronic Amplification & Speakers*
Tu. 3/19: Review **Th. 3/21:** Exam 2 (*Ch 8,9,16,6,17*)		**Mon. 3/18** or **Tues. 3/19:** Lab 10 *The Ear 1: Limits of Hearing*

Scan in book's cross-section of inner ear (Fig 6.4) & the plot of loudness countours as functions of frequency and SIL (Fig. 6.12)

Equipment:

- Water balloon in tube
- Ripple tank to demonstrate that high frequencies attenuate sooner
- Ppt of structure of ear
- Meter stick and pen
- Alan's resonance demo
- Light mass from stiff spring and big mass from soft one – both hung from same bar

Administrative:

Tests

- Test 1 is graded and available.
    - **Curve.** I did two things to curve the grades:
        - **Shift.** The high was something like a 96.5 – I shifted all grades up 3.5 to make that 100.
        - **Reweight.** to control for bad problems (say, confusing wording or subjects I'd not really prepared you for) I reweighted problems according to the fraction of points people got right – for example, if on average folks got only 50% of a problem's point, then it dropped from being worth, say 10pts to being worth 5pts. In general, this improves folks scores by a couple percent; if it would have hurt anyone's score, then I did not apply this to that person (don't want to penalize a person for actually getting the tough ones right!)

    So, the score written inside your test is better than the sum of the marks I made on individual problems – if you want to see exactly how I got from one to the other, feel free to drop by.

Presentations

- **Schedule.** I'll soon post a presentation schedule (I'll email out with a link). Note the day, topic, and colleagues (other folks that same day with similar topics) that I've suggested.
- **Guidance:** My conception of the presentations is that, for those 20min or so, you and your group are the 'guest teacher' – so it's not about proving to me and your classmates that you learned something about your subject, but about helping them to learn that something. This doesn't need to be an extensive research project; if you want to do some experiments and you find some good sources beyond the text – swell! However, if

you're talking about, say, violins and there's sufficient relevant material in the text that we didn't cover, you can draw from just that.

- **Be thinking about:** For the presentations, I ask that you select a reading for your classmates and a homework problem. These needn't come from the textbook, but if they don't please get me a copy so I can make copies for your classmates to distribute in advance.

Chapter 6 The Human Ear

This chapter has some great material in it. In introducing the Ear, it doesn't just talk about the Ear's taxonomy and mechanical function, it also starts to relate the things we *measure* in physics to the things we *perceive:* Loudness, Pitch, Timbre. Between this chapter and Thursday's reading, we begin to understand how these perceptions are related not just to Intensity, Frequency, and Spectrum, but to each other as well. Today, I'm mostly focusing on the mechanical function of the ear, and next time how that helps us understand the relations between our perceptions of sound.

- **Introduction:** The human ear is a wonderful instrument.
  - **Frequency Response:** It detects frequencies from 20 Hz to 20000 Hz, i.e., over a range of about 10 octaves. As you're probably aware, pure colors are light waves of different frequencies – we can see light of frequencies 2×10^{15}Hz to 4×10^{15} Hz, just one octave!
    - The book mentions that notes below 20Hz are more "felt" than "heard." Those of you who attended the University's inauguration, you may have noticed a few times during one of the organ pieces that *felt* a pressure throughout your body – that was the *low* note.
  - **Amplitude Response:** The quietest sound we can hear has a pressure amplitude 1,000,000 times smaller than the loudest sound we can withstand.
  - This is a highly evolved sensory organ. Not only does the ear translate the mechanical motion of the air into electrical signals to the brain (act as a transducer) but it also, mechanically, resolves complex mechanical motions into distinct pure tone components – Fourier Transform. Today we will look inside at its inner workings. The Ear is complicated enough that this will take two passes, so next time we will look at it in greater detail.

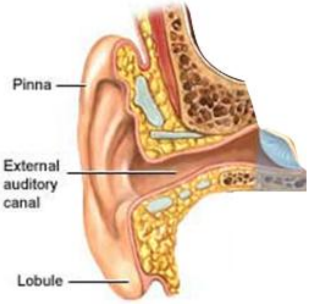
A complex sound is initiated somewhere in the room.

- The wave radiates out. If you are standing line of sight, some of the wave proceeds straight toward you and some of it reflects off surfaces toward you, constituting the first reflection.
- **Localization Cue 1: Comparing direct and Reflected Sound**
- **Localization Cue 2: Comparing onset times at the two Ears**
- **Localization Cue 3: Comparing sound phase at the two Ears**
- **Localization Clue 4: Comparing complex wave forms, front vs. back.**

6.1 The Mechanism of the Human Ear

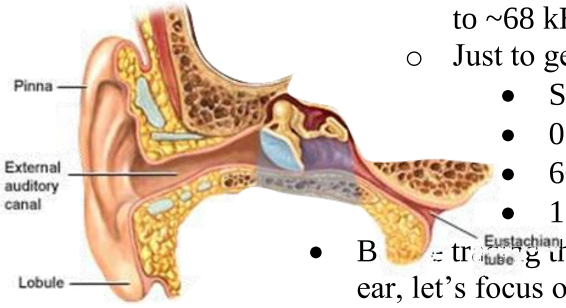
Introduction: Today we'll follow the mechanical motion of sound into the inner ear. We'll trace it until it gets transformed into electrical signals that are transmitted to the brain. Chapter 17, on Thursday, gets into more detail, but today we'll lay the basic groundwork. In so doing we'll see how the ear's construction enables it to mechanically Fourier Transform complex sound waves into combinations of pure tones. The description of this process falls under the heading of **Place Theory**. As we'll see, different parts of, or *places* in, the ear are sensitive to different frequency pure tones (thus the name of the theory).

Outer Ear – Sound Collection & Localization



- Sound first encounters the Pinna.
    - **Pinna** = outer protruding part of ear.
        - **Function:** Think of the Pinna as an asymmetric *diffraction obstacle* for short-wavelength / high frequency sounds. High frequency sounds coming from different directions will more or less easily make it into the ear – this is one of a collection of phenomenon that we subconsciously use to determine where the sound is coming from, but Mandy will probably get into this a bit more when she talks about localization. It also acts as a *funnel*, helping to gather and focus incident sound on into the ear.
- The wave moves on down the Auditory Canal
    - **Auditory Canal** (label on picture)

Middle Ear – Amplification



- At the end of the canal it impacts the Eardrum.
    - **Eardrum** = thin diaphragm, like that of a drumhead, speaker head, or microphone head. Radius around 0.5 cm. (so it could respond to sounds up to ~68 kHz!)
    - Just to get a sense for the Eardrum's response to sound

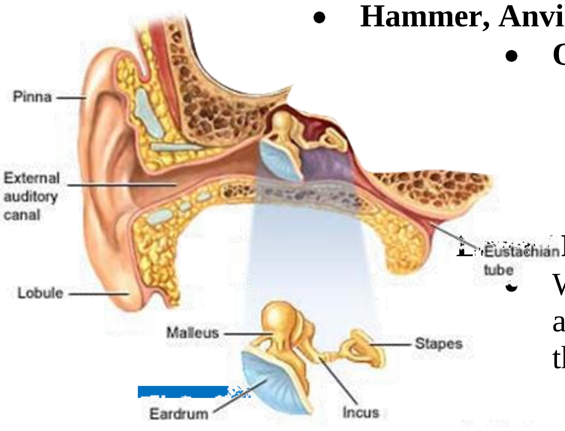
SIL	Displacement
0 dB	10^{-11}m (a fraction of an atomic diameter!!)
60 dB	10^{-8}m
120dB	10^{-5}m

- Before tracing the transfer of the sound's mechanical vibration deeper into the ear, let's focus on what allows the Eardrum to function properly.
- Immediately behind the eardrum is an open cavity which is connected via the **Eustachian tube** to the throat, which is open to your mouth and the outside world.
    - **Why?**
        - Say there wasn't a path to the outside world, just a closed cavity behind the eardrum. One day a high-pressure front comes through town, then the air outside the ear is at a higher pressure than that in the closed cavity. It's like a tug of war with one team much stronger than the other – the eardrum gets pushed in. Conversely, say you're hiking in the mountains, at a higher elevation, the air

pressure is less than down here. So the ear drum would feel a net push outwards.

- Note: **threshold of pain** corresponds to only about 2-3% change in air pressure.

- These scenarios present two problems.
    - **Pain.** One is that it can be downright *painful* to have the eardrum so stressed, and it could even be damaged.
    - **Less Responsive**. The other is that the eardrum, already stretched to its limits can't respond so well to the slight variations in sound pressure that constitute a sound wave. So hearing is impaired.
- **Q:** When have you experienced these symptoms?
    - **A:** Climbing a mountain, swimming, flying in a plane when you have a slight cold.
- When you've got a cold, the walls of the Eustacian tube can swell together – closing the passage from the middle ear cavity to the outside world. If it's not too bad, you can **'pop' your ears** by forcing the tube open briefly & allowing inner pressure to equilibrate with the outer pressure.



- **Hammer, Anvil, and Stirrup**
    - **Ossicles** = three tiny bones.
        - **Malleus** (hammer) connected directly to the Eardrum.
        - **Incus:** (anvil) Pressed against the other end of the Malleus.
        - **Stapes:** (stirrup) Bridging the gap from the Incus on to the 'window' into the Inner ear.
  - **Force Amplification**
    - When the Eardrum moves in, the Ossicles collectively pivot. They are anchored so that the Malleus moves about 1.3 times as far as the Stapes.
        - **Demo:** Meter stick and pen, joined together at an angle. When meter stick moves a great distance, the pen moves only a small one.
    - This geometry is that of a lever. If you've ever had to resort to a wrench to open something, or you've ever tried pushing open a door at the wrong end - you've observed that the further from the pivot point that you push, the lighter a push it takes to make the thing turn. The Eardrum is pushing at an end far from the pivot point of the Ossicles, so it has an easy job and it moves far. The oval window on the other hand is near in to the pivot point – so it feels a great force and moves little.
    - The math works that the forces and distances go inversely. The Eardrum pushes 1.3 times further out from the pivot point, so the Oval window feels 1.3 times the force.
  - **Safety mechanism: tensor tympani & stapedius muscles**
    - Restrict the motion of the ossicles if the sound is too loud
- **Oval Window**

- The stapes push on the oval window. It is a diaphragm that is about 20 times *smaller* than the Eardrum. Considering the relative pressures for a moment,

$$\text{In general, Pressure} = \frac{\text{Force}}{\text{SurfaceArea}} : P = \frac{F}{S}$$

$$P_{eardrum} = \frac{F_{eardrum}}{S_{eardrum}} \quad \text{similarly,} \quad P_{oval.window} = \frac{F_{oval.window}}{S_{oval.window}}$$

Where the forces and areas at the oval window are related to those at the ear drum by

$$F_{oval.window} = 1.3 * F_{eardrum} \quad \text{and}$$

$$S_{oval.window} = \frac{1}{20} * S_{eardrum}$$

Substituting these into our expression for the pressure at the oval window gives

$$P_{oval.window} = \frac{F_{oval.window}}{S_{oval.window}} = \frac{1.3 * F_{eardrum}}{\frac{1}{20} S_{eardrum}} = 26 \frac{F_{eardrum}}{S_{eardrum}} = 26 P_{eardrum}$$ where

the last step is recognizing that the ratio of the force and area at the eardrum is the pressure there.

- If the middle ear worked *perfectly* thanks to it, the pressure variations passed inside the ear would be 26-30 times greater than that of the sound impacted on the eardrum the intensity would be about 30dB greater, and we would be sensitive to sound 30dB quieter than without the middle ear. In fact we get about a 20 – 25 dB gain, pressures multiplied by about 10-20 times. We'll split the difference and us 15 as a representative value.

- **Example** Consider sound at the threshold of pain, about 150 dB, pressure fluctuations around 2500 N/m^2. a) how large would be the pressure fluctuations in the inner ear? B) how much would the eardrum move C) how much would the Oval Window move?
  - **A)** The pressure fluctuation at the inner ear is between 10 and 20 times greater than at the eardrum, so taking 15 times as the average.
    - $P_{inner} = 15 * P_{drum} = 15 * 2500\text{N/m}^2 = 37{,}500\ \text{N/m}^2$
  - B) Looking back at

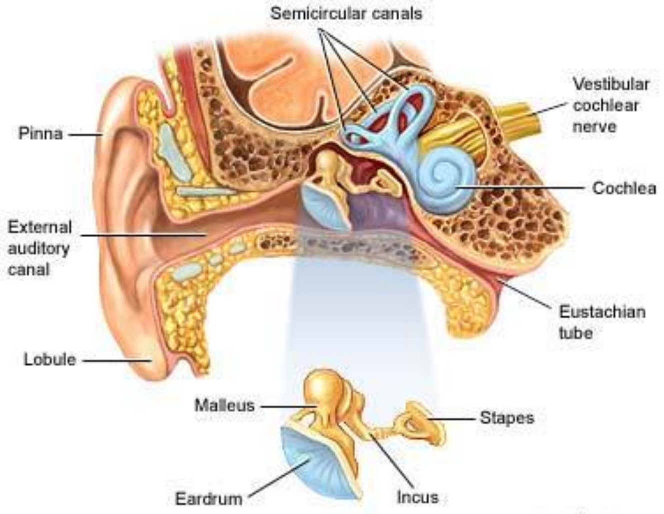
SPL	$\mathbf{D_{eardrum}}$
0 dB	10^{-11}m (a fraction of an atomic diameter!!)
60 dB	10^{-8}m
120dB	10^{-5}m

    - We see a trend of , for every 60 dB increase there is a 10^3 increase in motion. Following that, a 150dB sound is 30 dB above 120dB, so we'd expect maybe a $10^{1.5}$ increase in motion
    - $10^{-5}\text{m} * 10^{1.5} = 10^{-3.5}\text{m} = 0.3$ mm !
  - C) The motion of the oval window is about 1.3 times less than that of the eardrum, so it moves

        - $D_{ow} = D_{eardrum}/1.3 = 0.3cm/1.3 = 0.77cm = 0.24$ mm.
- **What's wrong with the calculated eardrum displacement?**
    - **Safety mechanism: tensor tympani & stapedius**
        - This is so large that the eardrum would be destroyed. Fortunately for us, we have muscles, **tensor tympani & stapedius,** in the middle ear that clamp the eardrum and stapes when the sound pressure gets too large, 90 – 100dB. They dampen out about 20dB worth of sound.
        - You've probably noticed that after a loud concert, everything sounds dampened. The muscles are still contracted, still holding everything in place.

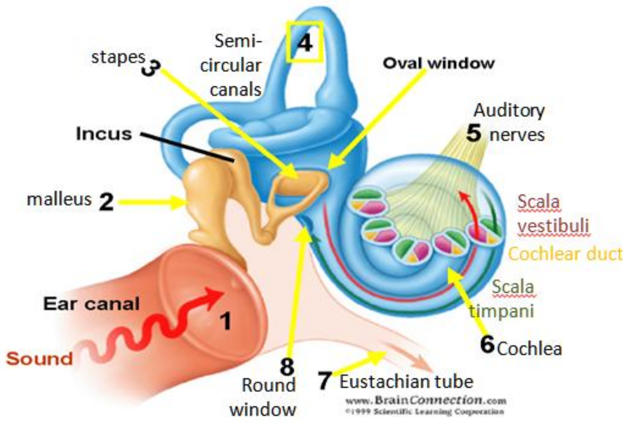
Inner Ear

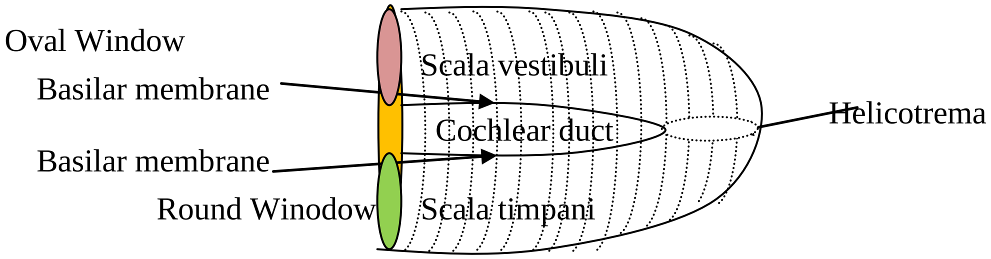
We follow the mechanical vibration of sound into the Inner Ear.



ADAM.

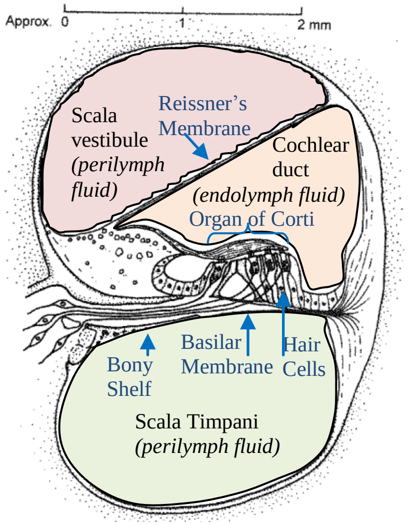
- **Semicircular canals**: looping canals containing fluid; they are nestled in curves in the surrounding bone. These don't have much to do with hearing, but they've got a lot to do with our sense of balance.
    - **Roughly how they work**: They are like carpenter's levels. They contain fluid & as they are tipped one way or another, the fluid shifts inside them. The fluid level is sensed & reports how 'level' your head is. So even with your eyes closed, you can sense whether you're tipping one way or another & thus you can try to right yourself.





(imagine uncoiling the cochlea)

- **Cochlea:** about a 3.5 cm long tapering, hollow tube that is coiled up. It is separated into three, fluid filled, halls that run the length of the tube. Roughly, one is on top, one is on bottom, and one is sandwiched in the middle. The top and bottom together are essentially one, long, U-shaped hall that has been doubled over. The **Oval Window** is a flexible membrane that 'looks' into the Scala vestibuli.
  - **Scala vestibuli** is the top section.
  - **Scala timpani** is the bottom section.
  - **Cochlear duct** separates the two.
  - **Helicotrema** is the doorway through which these two parallel scala are joined at the tip of the cochlea.
  - The Scala timpani has its own 'window looking back into the middle ear: The **Round Window.**
  - Essentially, there is one long, bent passage that runs from the Oval window down to the tip of the cochlea and back to the Round window.
  - **Perilymph** is a fluid that fills the whole outer passage.
  - **Endolymph** is more viscous fluid that fills the inner chamber.
  - Viscous = like motor oil or syrup: thick and slow running – individual particles of the liquid don't like to slide past other particles.
  -

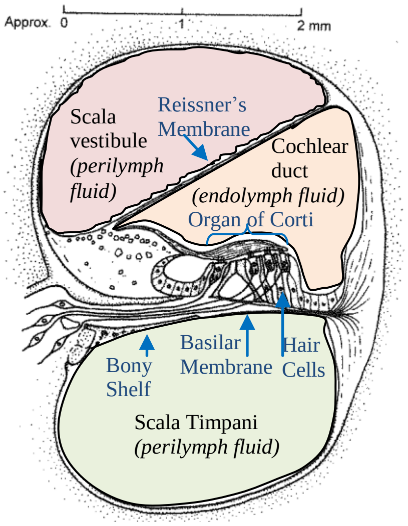


- **Follow the Sound**
  - So sound waves funnel down the outer ear to beat on the ear drum. The eardrum drives the bony contraption called the ossicles which in turn pump the oval window. Through Mechanical reduction of membrane size and through Lever action of the ossicles, we have amplified the sound. Now what?

- **Demo: Water balloon confined in a tube.** Push on one end. The push is transmitted *hydraulically* to the other end. The other end flexes.
  - Similarly, the oval window is pushed, that push is hydraulically transmitted down the length of the cochlea and back around to the round window. In turn, the round window flexes.
- **Role of Viscosity**
  - A viscous fluid is sluggish. If you suddenly *hit* something viscous, it pushes back almost like a solid, but if you slowly press on it, you can slide right through. Coherent motion, like a wave, easily degenerates into incoherent motion – just heat. This means that as waves ripple out from their source, they slowly degenerate and finally disappear. How far a wave makes it depends on its frequency. Qualitatively, if you ask the fluid to move up, no, down, no, up… changing direction very quickly, it just gets muddled and hardly moves at all.
  - **Demo** Drive waves on surface of wave tank. Dial up frequency and see them die off nearer and nearer to the driver.
  - **Apply this to the Perilymph in the Scalas vestibuli and timpani.**
    - **Low frequency** sound waves drive the eardrum-ossicles-oval window slowly. Thus the perilymph is slowly pushed in and back. This low frequency motion is transmitted relatively undiminished all the way to the Round Window.
    - **High frequency** sound waves drive the eardrum-ossicles-oval window quickly. Thus the perilymph is rapidly pushed in and back. The amplitude of this high frequency motion dies off dramatically as it is propagated from the Oval window toward the Round Window.
    - **Place Theory:** Here we encounter the first aspect of the ear which associates a *place* in the ear with frequencies.
- **Role of the Round Window**
  - But that just transmits the sound waves back through the round window into the middle ear, not on to the brain!
  - Indeed, the only reason for the Round Window is to give some relieve to the push on the oval window. Perilymph isn't very compressible, i.e., you can move it, but you can't make it smaller, so if it gets pushed in on the oval window it's to push out somewhere, and that's the round window.

So what path does the sound signal take into the brain?

- The *outer walls* of the cochlea do nothing more interesting than hold all the pieces together. But let's focus on the *inner* walls that surround the Cochlear duct.
- **Cochlear duct** is the inner hall, sandwiched between the Scala vestuli and scala timpani. It is filled with endolymph.
- **Endolymph** is an even more viscous fluid than the perilymph.
- **Reissner's membrane** separates the Cochlear duct from the Scala vestibuli above it.



- **Basilar membrane** separates the cochlear duct from the Scala timpani below it.
- Both of these are membranes are flexible. So, when the oval window is pushed in, not only does the push get transmitted via the fluid, down the long cochlea, through the Helicotrema, and around to the round window; it also get's transmitted striaight through the Reissner's Membrane, into the Cochlear duct, and on through the Basilar membrane. This is the short-cut from the Oval window to the Round window.
- **High vs. Low Frequency**
    - Now, since a high frequency wave dies off as it goes further along the cochlea, if not for its taking this short-cut, it wouldn't make it down to the scala timpani at all. As it is, it only makes it to the window-end of the cochlea. Meanwhile, low frequency makes it all the way along.
    - **Place theory:** This reinforces the viscous-fluid effect which associates high frequency vibrations with only the window-end of the cochlea.
    - **Simple Harmonic Oscillator Properties**
        - The association of high frequency with near window, and low frequency with the far end is excentuated by the fact that the Basilar membrane is *light* and *stiff near* the windows and it grows *heavy and flimsy* as it approaches the far end.
        - Recall from our discussion of harmonically oscillating systems that they have natural frequencies to which they respond best. That natural frequency depends on the interplay of a system's stiffness and mass as represented in $f \propto \sqrt{\frac{k}{m}}$. Light and stiff is a recipie for a *high* natural frequency; massive and flimsy is a recipie for a *low* natural frequency.
    - **Demo:** drive a light mass on a stiff spring and a heavy mass on a loose spring – see the difference in natural frequencies.
        - Thanks to this gradation in mass and stiffness along the basilar membrane, the natural frequency of vibration for a point on the basilar membrane is higher if it is closer to the windows and lower if it is further from the windows. These natural frequencies range from around 20 kHz to around 20 Hz (sound familiar?)
    - **Demo:** both mass – spring combos hang from the same bar & move the bare up and down, first in resonance with one mass-spring and then in resonance with the other.

    - Just as with the two mass-spring systems, of different natural frequencies, when a pure tone enters the cochlea, only the part of the basilar membrane with the corresponding natural frequency *really* moves up and down.
    - If a complex tone enters the cochlea, each pure tone of which it's built drives a different piece of the basilar membrane up and down.
- **Hairs**
    - In the Cochlear channel, floating just above the basilar membrane is the **organ of corti**. Here are rows and rows of hair cells. With out getting into any further detail, these are analogous to keys on your keyboard.
    - **Hairs ~ Keys**
        - When a region of the basilar membrane gets pushed up and down, it disturbs the hairs 'presses the buttons.' The hairs are 'wired' to **auditory nerve** fibers that run out of the ear and toward the brain. Just as when you strike a particular key on the keyboard, a particular electrical signal is sent to the computer and it interprets that as an "I" or a "Z", so when a particular hair cell is disturbed, an electrical signal is sent to the brain, and that's a "550 Hz" or a "320 Hz".
        - **Hearing loss side note**
            - We've all used beaten-up keyboards in our time, say the "s" sticks, or the space-bar just doesn't work. This came from excessively punishing typing, maybe someone habitually *pounded* on the keys. Similarly you can destroy you 'hearing keys' – the hair cells habitually *pounding* on them; by listening to really loud sounds.
    - So, the Basilar membrane vibrates up and down, pressing on / bending the hairs which are mounted in the Organ of Corti, and when these are bent, the nerve fibers that they're attached to fire off signals.
        - Note: Rossing points out that not all hairs are wired to nerve fibers, some are there simply to act like springs – when the basilar membrane presses on them, they flex, and push back, helping to amplify the motion of the basilar membrane and thus amplify the

sensitivity to the sound signal by about 40dB.

Perceptions: 6.3-.7

The main points to these sections are that our perceptions of sound: pitch, loudness, and timbre, are

a) Mostly our measures of *frequency, intensity, and spectrum* (in that order)
b) But, they are *not* linearly related (doubling intensity isn't doubling loudness)
c) And they are slightly dependent upon each other.

Just Noticeable Difference.

- **Frequency.** This 'typing' of notes on the hairs in the inner ear is, of course, a bit of a simplification. For one thing, it's not like just one little patch of the Organ of corti or Bailar membrane can move all by itself; there's a spread of motion. So it's really a broad distribution of hairs that get excited and send signals to the brain. Chapter 17 goes into a little more detail, but this makes it plausible that we really can't discern too small a difference in frequency.
    - **Intensity.** Similarly, we can't judge too fine a difference in Inensity.
    - **Next week's lab.** In lab next week we'll experiment with these a little.A better analogy might be typing *in mittens:* you don't just hit one key, you hit a whole patch of keys.you want the "D", you hit E,R,S,D,F,X, C. It's up to the brain to decipher this mess being D.

We'll work with this a bit in lab next week, but one quick example of the inter-dependence of our perceptions of pitch and loudness is figure 6.12. Following any one curve (perceived loudness), you can see how the actual intensity required (left axis) varies with the frequency played (right axis.) Some features we can pull out are that we are most sensitive to frequencies around 3500 Hz; for example, to perceive a sound as 70 Phones loud at this frequency, it only needs to have an SIL of 60dB, but at100Hz, it would need to have an SIL of 75dB.