Tu., 1/11 Wed., 1/12 Th., 1/13	**Ch 1** The Nature of Sound **Lab 1** *Oscilloscope & Speed of Sound* (2.1,.2, 8.1) **Ch 1** The Nature of Sound	HW1: Ch1: 9, 11, A, B
Tu., 1/18 Wed., 1/29 Th., 1/20	**Ch 2** Waves and Vibrations **Lab 2** *Harmonic Motion* **Ch 2** Waves and Vibrations	HW2: Ch2: 1, 20, Project (choose one from p37 and turn in 1page write-up)… Ch2: 12, 24

Materials

- Bell-jar with pump & bell
- Transverse Wave machine with water can for damping
- Simulation of compression /rarefaction passing through gas?
  - http://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html

- Hanging slinky?
- Matches (and candle to make it even better)
- Balloon **or** Marshmellow
- Evacuatable sphere
- Molecules.exe
- Clickers and transmitter

About 1hr set up and 45min tear-down

Set-up

Longitudinal Wave machine
Log on as me, bring up Molecules.exe and then A/V mute

Who's still waiting on a text to arrive? (provide copies of Ch 2.)

Office Hours: Th/F 2:30 – 3:50

Last time

Sound is a process of *production*, *propagation, and perception.* It is *produced* when something mechanically vibrates. If the vibrations are within the range of about 20 Hz to 20 kHz, we *perceive* the rate of vibration as *pitch* and the amplitude as *loudness.* Later, we'll get into *perception* a good deal more, but today,..

Propagation

…we're going to be thinking about how the sound gets from where it's produced to where it's perceived: **Propagation**
Along the way, we'll introduce / develop some useful ideas / tools.

How do the vibrations of sound get *between* of the throat, string, speaker head,… and our ears?

Q: What material is there *between* the source and the eardrum?
A: Air.

To hear the degree to which the air is important in this process, let's remove it from between us and a sound source and note whether or not it sounds any different.

Disclaimers: a) we won't remove *all* the air and b) the bell is still touching the glass dome, via the springs, and so able to transmit some sound. So we don't expect it to go *completely* silent.

Pre-Demo: What will happen to the sound we hear as I remove the air?
(note: some students will predict it gets louder, some quieter, some no-change; could make a clicker question)

Demo: Bell jar with a bell in it, ringing; with air, without air, then with air again (for the second transition, can have the pump off so its noise doesn't mask the bell.)

Obviously, the air is *key* to the propagation of sound from source to ear. In fact, if there were perfect vacuum between the source and us, we wouldn't hear anything at all! (though that doesn't stop Hollywood from having the sound of exploding space ships rock nearby ships.)

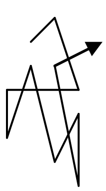
Air

To understand how sound propagates through air, we first have to understand air. So, let's think about air a little bit – what it's made of, what it's invisibly doing…

Q: Of what is air composed?
A: A gas of small molecules:
~ 70% N_2, ~20% O_2, …
Q: what is a 'gas'?
A: A sparse collection of particles, each one zipping straight from collision to collision, like a 3-D swarm of bumper cars, or slam-dancers in a mosh-pit. These particles have no minds of their own, so one just zips straight ahead until it rams into another one and the two ricochet off each other, like pool balls, in some new directions.

Demo: Molecules.exe

- **Air properties**
  - **Density:** how closely packed the air particles are – are they almost right on top of each other, or are they pretty far apart. This is generally measured in particles per volume. There are roughly 2.55×10^{25} air particles in a cubic meter of this room: density = 2.55×10^{25} particles/m^3.
    - **Separation:** So the average separation of particles is around 3.4×10^{-9}m; that's about 10 times as far apart as atoms are when their bound to each other, like in a solid. So, if my fists were molecules of air, the distance between them would be about a yard.



  - **Temperature:** Of all the common physical properties, temperature is perhaps the least fundamental / hardest to describe in fundamental terms. For our purposes, it determines how energetically gas particles zip around.
    - The warmer it is, the faster they zip. (in **Molecules.exe**, turn up the energy)
    - The colder it is, the more sluggish they are. (in **Molecules.exe**, turn down the energy)
  - The average air particle in this room is moving about 500 m/s ~ 1,100 mi/hr! But of course, they hardly get anywhere since they are so closely packed that they are always colliding and bouncing off in new directions.

- **Collisions per second.** Putting the speed and average separation together, we're looking at one atom having about 150 Billion collisions a second!

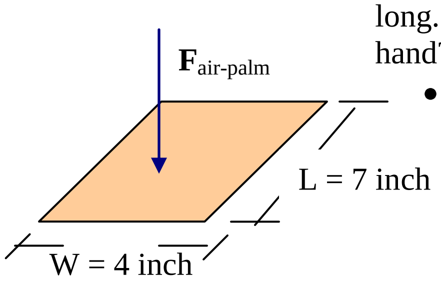
- **Pressure:**
  - Of course, with all those collisions, there's an awful lot of pushing going on. For example, in our simulation focus on all those 'atoms' bouncing up against one of the wall. While they're each pretty small / individually they don't pack much of a punch, there would be *so very* many of them bouncing against the wall per second that it all adds up.
  - **Pressure =** the push per area.
  - Air pressure is about 10^5 Pascal = 10^5N/m^2 = 14.70 lbs/inch^2.
  - **Compressive force on you.** That may not sound like a lot, but consider how many square inches of surface area you have: about 2, 600 inch^2. So about 40,000 lbs of force are compressing you right now! Since this is applied on us from every direction, it doesn't act to push us one way or another, but ever wonder what would happen if half of it weren't there?

Demo. Balloon in vacuum.

  - **Force:** Talking about "pressure", I've invoked another idea, "Force." To a physicist, "force" is our measurement of a pull or push – how strong it is and, for that matter, in what direction it is.
    - **Units:** The two common systems of units, either use the Newton, N, where 1 N ~ the weight of an apple, or pound, lbs, and we're all familiar with our own weight.

- So, **P = F/S,** the pressure on an area is the force applied to it divided by the area.

This idea of pressure will come up a lot, so let's pause and do a little work with it:



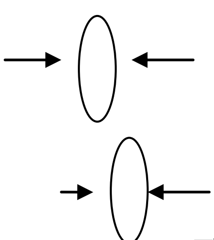
- **Example**: My palm measures about 4 inches wide and 7 inches long. So what is the force of air pressing into the palm of my hand?
  - **Quantities**:
    - **W =** 4inch palm's width
    - **L =** 7 inch palm's length
    - **A** = ? palm's area
    - $\mathbf{P_{air}}$ = 14.70lbs/inch^2
    - $\mathbf{F}_{air\text{-}palm}$ = ?
  - **Relations**
    - $S_{palm} = W_{palm} \times L_{palm}$
    - $P_{palm} = \dfrac{F_{palm}}{S_{palm}}$
  - **Algebra**
    - $P_{palm} = \dfrac{F_{palm}}{S_{palm}} \Rightarrow F_{palm} = P_{palm} \times S_{palm}$
    - $S_{palm} = W_{palm} \times L_{palm}$
    - $F_{palm} = P_{palm} \times (W_{palm} \times L_{palm})$

- **Numbers**
  - **F_{palm} = 14.70lbs/inch^2 (4inch × 7 inch)= 411.6 lbs**
  - Fortunately, the air is all around us, so there is an equal force pushing on the back of my hand as on the front, so my hand is just sandwiched in-between. Like having two matched teams in a tug-of-war – because the rope has the same pull in both directions, it doesn't take off in either direction.

Here's an example where that force *isn't* balanced:
Demo: evacuate cylinder and try to pull apart.
Since this has a cross-sectional area of about the same as my hand, the force holding it together is roughly 400 lbs!

Clicker Question:
The area of a circle is $S = \pi r^2$ where π is 3.14…. and r is the radius of the circle. The inner radius of this sphere is about 3.5 cm. So if it's almost completely evacuated / no air inside, what's the force holding it together?

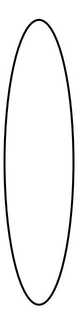
A. 38,000 N = 8,700 lbs
B. 380 N = 87 lbs
C.11,000 N = 2,500 lbs
D. 2,500 N = 570 lbs
E. "I didn't get any of these values"



Pressure and the Ear. When we get into the anatomy of the Ear, you'll see that just inside the ear, behind the eardrum, is air, at ambient air pressure. In silence, the pressure on both sides of the eardrum is the same, so the push into the ear = the push out of the ear, just like the push on the palm of my hand is the same as the push on the back of my hand. But when there is sound, the air outside pushes just a little more during a compression, and pushes just a little less during a rarefaction. These result in a net push into the ear or out of the ear. The book points out that the drum is sensitive to pressure differences 1000th to 100,000th of a percent!

That brings us back to our main focus of the day – how sound propagates through air.

Sound Propagating through air
- Start with the diaphragm of a speaker, on one side and the diaphragm of your eardrum on the other, with air in between. We'll go step by step, watching how the different motions of the speaker propagate to the eardrum.
- **Bouncers and Mosh pit analogy:** Analogously, start with a line of bouncers along one side of a mosh pit, and a line of bouncers along the other.



  - The dancers are just bouncing off of each other and off of the bouncers. They're bouncing fast and hard, but the floor is so packed, that they really don't get anywhere.
  - **Compression: "**front" where the density and pressure is increased.

        - Say the first line of bouncers pushes into the crowd, pushing on the dancers right by them: creating a front of increased density, increased pressure.
        - The dancers right by them collide extra hard with them and bounce off into their neighbors extra hard. Those neighbors bounce into the *next* set of neighbors extra hard,…, eventually this push makes it all the way across the floor to the other line of bouncers and that line is pushed out.
        - This represents one push of air from the speaker head to the ear drum.
    - **Rarefaction:** front of lowered density and pressure.
        - Say next the first line of bouncers now step way back *out* of the crowd.
        - The dancers just beside them all of a sudden have a little more room to move, and they move back.
        - The dancers beside them now have a little more room, and they spread out…this goes all the way to the other line of bouncers, so they are no longer pushed out, they actually come in a little.
    - **Demo: hanging Slinky Compression - pulse**
        - **Intro:** Like the air, a slinky can be compressed, so the coils are closer together than normal, and rarefied, so the coils are further apart than normal. When the coils are too close, their springiness pushes to separate them, when they are too far, their neighbors push them back together.

    - **The pulses propagate, but the medium does not**
        - No piece of the slinky moves that far, but the pulse is transmitted from coil to coil.
        - Similarly, no individual mosh-pit dancers makes it all the way across the dance floor, each one moves just a little. It was the *push* that moved across the room, transmitted from dancer to dancer.
        - **Demo:** light match and extinguish. Speak through the smoke. While the sound makes it across the room to you, the smoke stays here.
    - **Speed of Sound**
        - With what speed does the pulse of compression move through the air?
            - First, let's get familiar with "speed"
            - **Speed**: v, change in position / change in time.

              $v = \frac{x_f - x_i}{t_f - t_i} = \frac{\Delta x}{\Delta t}$ where x_f is the final position, x_i is the initial position, t_f is the final time and t_i is the initial time., the deltas read "change in."

- **Example:** I drive from here to my brother's house in Pasadena, a distance of about 100 miles, and it takes me about 80 min. What was my average speed?
  - $v = \frac{x_f - x_i}{t_f - t_i} = \frac{\Delta x}{\Delta t} = \frac{100mi}{80\min} = 1.25\frac{mi}{\min}\cdot\frac{60\min}{1hr} = 75mph$

- **Or, a further example (not dissimilar from a homework problem:)** Say I were a law abiding instead and drove 65 mph the same 100 miles; how much *later* would I arrive?
  - Well, we already know it would take me 80 min if going 75mph, let's call that $\Delta t_{75} = 80\min$. Going those 100 miles at 65 mph would take me
  - $\Delta t_{65} = \Delta x / v_{65} = 100mi/(65mph) = 1.54hr * 60\min/hr$ $= 92.3\min$
  - So the difference would be $\Delta t_{65} - \Delta t_{75} = 92.3\min - 80\min = 12.3\min$
-

- Now for the **speed of sound.** We won't fully derive the expression (beyond scope), but motivate some character of it.
  - Imagine again the dance floor full of slam dancers. Previously, I'd exaggerated the effect of the bouncers pushing in, in fact, relative to how vigorously the dancers are already slamming around, the bouncers push when they step in (the speaker-heads' push when it pushes on air) is miniscule. Perhaps a better picture is that the "speaker" line of bouncers along the left side of the dance floor just hand the dancers a note card, and when those dancers, in the natural course of zipping around, bounce into the folks to their right, they hand them the note cards, etc. until the note cards make it all the way across the room.
  - So the speed with which the note card gets passed, really depends on how quickly the individual dancers are already moving. If they're flailing around to really fast music, the note cards make it across pretty quickly, but if it's a slow dance, it takes quite a while. In this analogy, the music is determining the rate of the dancers motion & thus the speed of card travel. The music is playing the role of temperature. The warmer a gas is, the more violently, the more quickly, the gas particles zip around, and so the sooner they bump into each other, and the sooner they pass on the slight push of the speaker.
  - Mathematically:

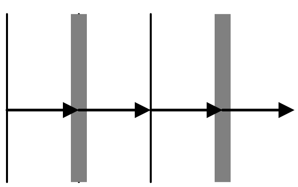
$$v_{sound} = \sqrt{\frac{\gamma kT}{m}}$$

- Where T is the air's temperature, m is the mass of the average air particle (around the 4.80×10^{-26}kg of N_2), k is essentially a conversion factor, like that converting between ft and m. $\gamma \sim 1.4$ is a constant that reflects the ways in which the particle can move (up-down, left-right, front-back, and, for the dumbbell of nitrogen can spin (room temp is too cold for vibrating)).

- **Physics Aside**: Recall from Thermodynamics and Kinetic Theory that the average kinetic energy associated with motion in one direction is $\langle \frac{1}{2} m v_x^2 \rangle = \frac{1}{2} k_b T$. Solving for the rms speed in one direction, you nearly get the speed of sound.
- There are some key pieces we've yet to develop, but I just want to hint at some of the repercussions of this relationship.
  - **Temperature dependence of wind instruments:** When we start talking about how different instruments produce sound, we'll see how this makes the tuning of wind instruments quite sensitive to changes in air temperature.
  - **Mass dependence:** We'll also come to understand how the speed's molecular mass dependence is responsible for the Mickey Mouse voice you get when you breathe helium instead of air.

- Aside from the Mickey Mouse voice, we're always going to be talking about air, and we're always going to be talking about temperatures *around* 0 to 100 C. So we can make this equation specific to our needs and exploit a mathematical tool (Taylor Series) to approximate this function as linear in T:
  - $v_s \approx 344\, m/s + 0.6\, m/s{\circ}C \times (T - 20{\circ}C)$ where T is measured in Centigrade / Celsius
  - $v_s \approx 344\, m/s + \frac{1}{3}\, m/s{\circ}F \times (T - 68{\circ}F)$ where T is measured in Fahrenheit.

- **Example: Minnesota vs. California sound**
  - About this time of year, it can be around 0°F in Minnesota; meanwhile, it's gotten up to nearly 70°F here these last few days (one reason I'm happy to have left MN behind.) What's the speed of sound here, and what is it in Minnesota?
    - **Quantities**
      - T_{MN} = 0°F
      - T_{CA} = 70°F
      - $v_{CA} - v_{MN}$ = ?
    - **Relations/Algebra/Numbers**
      - $v_{s.CA} \approx 344\,{}^{m}\!/\!_{s} + \frac{1}{3}\,{}^{m}\!/\!_{s^\circ F} \times (T_{CA} - 68^\circ F)$
        $v_{s.CA} \approx 344\,{}^{m}\!/\!_{s} + \frac{1}{3}\,{}^{m}\!/\!_{s^\circ F} \times (70^\circ F - 68^\circ F) = 344.7\,{}^{m}\!/\!_{s}$
      - $v_{s.MN} \approx 344\,{}^{m}\!/\!_{s} + \frac{1}{3}\,{}^{m}\!/\!_{s^\circ F} \times (T_{MN} - 68^\circ F)$
        $v_{s.MN} \approx 344\,{}^{m}\!/\!_{s} + \frac{1}{3}\,{}^{m}\!/\!_{s^\circ F} \times (0^\circ F - 68^\circ F) = 321\,{}^{m}\!/\!_{s}$
    - **Note:** These speeds differ by about 6.5% - so we'll later see that wind instruments would experience a 6.5% shift in pitch.
- **Vibrations & Waves**



  - So far, we've pictured one compression or one rarefaction making its way across a room / dance floor. We, as humans, aren't built to *hear* that. It's the repeated compressing & rarefacting: the speaker head pushes in, pulls back, pushes in, pulls back. Each time the head pushes in, it launches a compression which speeds away at v_s. Each time it pulls back, it launches a rarefaction which speeds away at v_s. Doing this over and over again launches a series of rarefactions and compressions. This series of disturbances propagating through a relatively stationary medium is called a **wave**. From the perspective of individual air molecules, each one cycles through participating in increases in pressure / density, and decreases. From the perspective of these fronts of pressure / density, they travel through the air.

Demo: Hanging slinky waves

Particularly since this slinky is a little worse for ware, it's a little messy, so we'll look at a cleaner, if less analogous, example.

Demo: Transverse Wave machine (with water can to dampen reflections.) Each pulse moves down the beam at the same speed, so, once a pair of pulses is launched, they don't get any closer or further from each other as they go. The separation between two pulses in a wave is the "wave length". Clearly, if I jiggle things more rapidly, the separation is smaller, and if I jiggle more slowly it's longer. In lab you've already used this relation,

$v = f\lambda$

*wave speed = frequency * wavelength.*

We’ll do more to really develop and understand it next week.

For next time: Speaking of Next week – read Chapter 2, see you on Tuesday, but don’t forget to do the homework, and feel free to drop by this afternoon (1:30 – 4:00) or any time Friday