Tu. 1/22: Ch 3 *Sources of Sound* **Th. 1/24:** Ch 3 *Sources of Sound*	HW3: Ch3: 2, 3^w, 7^w… Ch3: 8^w,9^w Project 1	**Mon. 1/21** or **Tues. 1/22:** Lab 3 *String Instruments: Vibrating String*(7.4, 10.1)
Tu. 1/29: Ch 4 *Sound Propagation* **Th. 1/31:** Ch 4 *Sound Propagation*	HW4: Ch 4: 1,3,4, Project… Ch 4: 8^w,10^w,11^w, 13	**Mon. 1/28** or **Tues. 1/29:** Lab 4 *Wind Instruments: Vibrating Air* (11.3, 12.1)

Materials

- **Toy Guitar**
  - Pick and bow
- **Wave tank**
  - taper and long bar and projector
- **Music box**
- **Violin shaped plate**
  - Pasco Driver, function generator (set around 90-300Hz), sand shaker, and box lid (like paper reams come in) to catch the sand
- **Computer set for http://www.falstad.com/circosc/, PhET –** waves on string(free end)
- **Circular plate**
  - Again, Pasco Driver, function generator (set around 90-300Hz) and sand
- **This week's lab equipment handout**
- **Torsion bars**
- **Variable length Organ pipe**
- Metal Organ Pipe
- **Recorder (the plastic musical instrument)**
- **Hanging Slinky**
- Symbol or nice big pot lid

Last Time: began Chapter 3 Sources of Sound

The common elements of making musical sounds

- Common to all musical instruments are three important steps in producing music.
  - 1) The a-tonal impetus of motion, the strike, pluck, or blow
  - 2) Tuning the non-musical vibration into specific frequencies
  - 3) Amplifying the motion for creating louder sound.

2) Tuning

Last time, we focused on how an instrument tunes – takes the a-musical impetus and produces a musical sound. Generally, that relates to resonance – that, given the geometry and material of the instrument it will vibrate at only specific frequencies.

String instrument.

More specifically, we considered stringed instruments and how the wavefront from a pluck can speed down the string, reflect off its fixed ends, speed back and forth, all along interfering with its reflections to produce a standing wave which ‘fits’ on the string. We didn’t rigorously walk through the whole process, but hopefully made it plausible.

We got quantitative about the frequencies that could be produced by a string by using the general relationship between frequency, wavelength, and wave speed for any wave and the relationship between wave speed, tension, and mass density specific to a wave on a string:

$$f\lambda = v = \sqrt{\frac{T}{\mu}}$$

And by observing that the only simple waves that ‘fit’ on a length of string have wavelengths

$$\lambda_n = 2L/n \text{ where } n = 1, 2, 3,\ldots$$

Putting these two together gives us the family of frequencies

- $f_n = \dfrac{n}{2L}\sqrt{\dfrac{T}{\mu}}$, n = 1, 2, 3,… **harmonic series**

- **Stringed Instruments**
  - Last time I spoke generally about strings, now let’s think more specifically about stringed instruments. We’ll see that each parameter on the right hand side of this equation gets addressed when building, tuning, and playing a stringed instrument.
- **Demo: Toy Guitar**
  - **Setting frequency response**
    - **Construction**
      - **Mass density (μ)** - Different strings of different mass densities and thus wave speeds
    - **Tuning**
      - **Tension (T)–** wave speeds
    - **Playing**
      - **Length (L) – fingering –** wave lengths
      - **Harmonic (n) –** playing harmonics is gently placing a finger on a string where you want a node to be, but not clamping it down so hard as to prevent the whole string from supporting the standing wave.
    - **Location & type of impetus (strike, bow…)** When a string is played, the fundamental frequency vibration dominates, but all other harmonics are also excited and heard faintly, giving ‘color’, or timbre, to the note that’s played. More subtly, the player can influence this timbre / how strongly the different harmonics are excited / heard by varying the attack / impetus.
      - **Type**
        - **Pluck-quick –** particularly excites high-frequency harmonics

        - **Strike – slower release –** dampens out high-frequency harmonics
        - **Bow – periodic release –** as the string vibrates back and forth, it's caught and released by the bow.
    - **Location** – wherever you drive the string, you enhance harmonics with anti-nodes there / reduce ones with nodes there

This Time

- **Mechanical Amplification**
    - Starting at our ear drum, we can trace the sound back to the source and see how it can change to make the sound louder in our ears.
        - The harder air pushes into our eardrum, the louder we perceive the sound to be. Thus the air just outside our ear must be getting pushed hard. Tracing back, the air at the source must be getting pushed hard.
            - **Amplitude** of the source's motion.
        - **Necessity to move a lot of air.** But if the source is moving terribly violently in vacuum, as we heard with the bell in the bell jar (or rather not heard) no sound gets transmitted. So it's not just a matter of how much the object, say, guitar string, moves but how much *air* it knocks around as a result. To push more air, the source should be bigger.
            - **Source Size.**
            - **Demo: Wave tank**
                - First wiggle water with just a finger
                - Then wiggle water with the whole beam – same amplitude of motion, but hitting more water – bigger waves.
        - **Sounding Board.** String instruments have a real problem - Strings are *small*, and so don't bump into a lot of air, but they can be anchored to something that is *much larger*, when the string vibrates, it drags this something, sounding board, with it.
            - **It's the bridge, not the hole**: there's a common misconception that the hole in a guitar is where the sound 'gets in or out' – the hole itself is of secondary concern; the primary communicator is the *bridge* – the strings yank back and forth on the bridge as they vibrate, and that transmits the vibration to the front plate (and through a post in violins, the back plate.)
        - **Demo:** Similarly, this music box isn't very loud on its own – just the metal tines vibrate, and the metal body a little, but… it's much louder when anchored to something big like the table – now the

table top is vibrating too, and that pushes around a lot more air – louder sound.

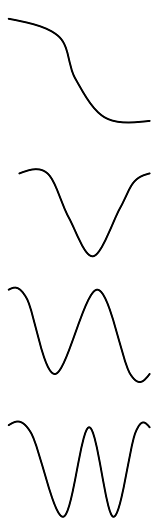
- **Resonance board / cavity colors sound.** But the table doesn't *just* amplify the sound, because it too, like the tines themselves, has frequencies at which it naturally resonates, so it tends to respond particularly well when driven at those frequencies and not so well when driven at other frequencies.
    - **Demo:** play music box on table, wooden box, wall, chalkboard, and footboard where chalkboards hide.
- **Visualizing resonance board motion.**
    - **Demo: violin back**
        - The dust gathers where the plate isn't jumping so much – at the nodes. – our violin-back plate has nice resonances around 90 hz – 300 hz
- Now, the resonances of a complicated shape like a violin back are, well, complicated. Let's consider something simpler, like a nice round drum head.

3.1 Percussion Instruments

This brings us to percussion instruments – their tuning elements are these 2-D boards. But being 2-D instead of 1-D, they have much more freedom about how they wiggle, and a more complicated relationship between the different frequencies at which they can wiggle which is to blame/thank for their not generally souding so 'musical' as string or wind instruments.

- **Drum –** A drum head is anchored all around its edges, much like a string is anchored at its edges. So, you can imagine what some of the simple modes of oscillation might look like: See Pg. 165 and 166 of your text
- **Demo: http://www.falstad.com/circosc/ (select display 2D+3D)**
    - 'fundaental' – the middle bows in and out
    - '1st harmonic' – the two sides 'slosh' up and down
    - cut into quarters, cut into sixths,…
    - concentric rings,…
- **Demo: circular resonance plate**
    - This is more like a symbol than a drum head in both material (metal) and that it's rim is free to flop.

Different boundary conditions – free end.



- Now, in contrast to the drum head, a symbol is *free* at both ends. At first blush, that might make you think that there are *no* boundary conditions and any old wave-length oscillation could be supported. But that's not the case, and this is an important point not only for symbols, but for many wind instruments, so we'll develop this carefully.
- **Demo: Pulse reflected off free end – torsion bar, PhET wave-on-a-string** This time the mass on the left end doesn't have a buddy holding it back when the wave comes from the right. So it moves extra easily, extra high. The wave pulse is reflected right back, right-side-up.

  - **Demo: Standing wave with free ends (driven in the middle)**
    - **Try to drive a few different frequencies.**
    - This is like a cross-sectional view of a disc
  - Like a string with fixed ends, this one, with free ends can support a family of wavelengths, this time, they must satisfy the condition that there are **anti-nodes** at the ends.

  - This too gives a simple, integer relationship between the wave-lengths, and therefore the frequencies that can be supported
- **2-D surface oscillations**
  - So, the symbol can support a very similar family of vibrations to a drum head – they're just anti-nodes instead of nodes at the edges.
    - Voltage around 0.6 V; First few are in range of 350 to 900 Hz, step by 10 Hz (when you find you're close to a mode, you can switch down to 1Hz resolution to zero in.)

  - **Impetus – Strike**
    - At first blush, the strike enforces no particular frequency, allowing the drum or cymbal to vibrate at its whole family of frequencies; however, there is a little selectivity.
    - **Stick vs. mallet**
      - Sometimes a hard headed stick is used, sometimes a soft mallet. This is similar to the difference in plucking a guitar string with a pick vs. hitting it with a felt covered hammer as in a piano. The larger and softer texture adsorbs some of the higher-frequency / shorter-wavelength vibrations – dampens them out. This leaves a sound that is dominated by the low frequencies. Not as bright.
  - **Frequency Selection**
    - A drum head is fixed at both ends, so its wave must fit the condition of nodes at the ends, like a string with fixed ends.
    - **Construction**
      - **Radius**: The drum head's radius plays a similar role to a string's length in selecting the frequencies, so bigger drum heads can produce deeper tones.
      - **Stiffness:** Changing the material and its thickness changes its elasticity / stiffness – like changing the tension in a string
      - **Mass density:** Again changing material and thickness.
    - **Tuning**
      - **Tension** One can adjust the tension of the drum head

        - **Playing**
            - **Location of strike** Where you strike it is guaranteed to be an anti-node / not to be a node. Look at the patterns we found. See which ones can all agree on a node or anti-node location.
                - Ex. Strike in the middle, and get less response from any thing that has an anti-node through it.
                - Strike near the far edge and get a lot of high frequency patterns.
    - **Amplification**
        - The cymbal or drumhead is already quite large. It needs very little help pushing the air around.

  - **Additional Tuning**
    - This falls under the heading of tuning done during the design and construction of an instrument, but I waited to mention it because it leads into wind instruments.
    - The drum head is typically suspended over a hollow cylinder. In some instruments that cylinder is open and in other it is closed (ex. Timpani). The air in that cavity is another medium which can vibrate. In the extreme of a xylophone, the air in the pipe below the bar has its own natural frequency. In the case of the kettle drum there is some resonance effect, but also the air provides a cushion – dampens out some higher frequencies.
    - The role of air *inside* an instrument brings us to the winds.

- **Not *exactly* harmonics –** Now, since a drum has a lot more freedom to oscillate, all those don't happen to be members of a simple harmonic series, some of them are close, some of them are not so close. So it's not so 'musical' sounding as, say, plucking a string. Still measures can be taken to select the sounds that it produces
  - **Membrane thickness.** varying the thickness of the membrane – lowering the frequencies that move these locations a lot / raising the frequencies that bend these locations a lot.
  - **Resonance cavity.** Mounting resonating cavities beneath like a kettle drum's to emphasize particular frequencies.
  - **Location of hit.** Striking in particular locations to excite particular vibrations

3.2 Wind Instruments

The common element is a resonance tube. The active element here is actually the column of air contained inside. This plays an analogous role to that of the string in the stringed instrument.

Air Column

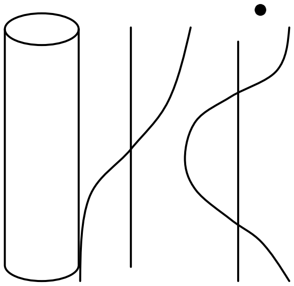
- **Wave speed:** The speed of a wave in air is determined by the air's properties (Temperature, that it is air after all, and not Helium), in particular, the general expression shows the same kind of interplay between inertia and some sort of restoring force as we saw for waves on a string: $v = \sqrt{\frac{\gamma k T}{m}} \Leftrightarrow \frac{\text{restoring}}{\text{inertia}}$; while it's nice to see that old theme playing out in this equation, given the temperatures that we'll be interested in, a more useful approximation is

$$v \approx 344\,{}^{m}\!/_{s} + (T - 20°C)\,0.6\,\frac{{}^{m}\!/_{s}}{°C}.$$

- **Wavelength.** We will see that the length of a column of air also determines the wavelengths that it can support.
- **Harmonics.** These correspond to a harmonic series of frequencies.

Standing waves in air

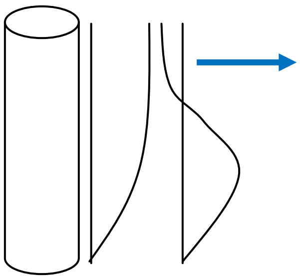
- You've *seen* standing waves on a string and seen evidence of standing waves on a surface like a drum head. But what about in air?
- **Sound wave – pressure, density, displacement wave.** A sound wave is characterized by a few simultaneous distortions in the air. There is series of pushes that get passed through the air – pressure distortions. In response the air moves – displacement. The air moves to bunch up or spread out – density distortions. The easiest for us to think about now is the displacement of the air. When a sound wave front passes through, some of the air molecules get *pushed ahead* into their neighbors, they then get *pushed back* by those neighbors.
- **Demo: Compression pulse in a slinky**



- **Boundary condition – open at both ends.** Some instruments are pretty open at both ends – the flute and some organ pipes. Now, one might wonder 'what's so different about the air *in* the instrument vs. the air *outside* the instrument?' The important difference is that the air inside is *more confined.* Imagine standing outside and clapping once; the sound pulse of that clap would radiate out in all directions, but if you clap at the end of a tube, the sound can only travel down the tube. When it gets to the end, it can finally spread out. That change from being confined to propagate in 1-D to being able to radiating out is enough to cause a reflection. An open end of the instrument will necessarily be were the air is *freest* to displace – a displacement anti-node. Then a familiar line of reasoning tells us that there is a harmonic series of air waves that can be supported in the tube.
  - **Demo: open Organ Pipe,** flute**.**
    - Overblowing will excite 2^{nd} harmonic

Just as for a string that's anchored at both ends, the open-ended tube supports waves that 'fit', have an integer number of half wavelengths along the length of the tube:

$L = \frac{\lambda}{2}, 2\frac{\lambda}{2}, \ldots \Rightarrow \lambda_n = \frac{2L}{n}$ and the corresponding frequencies that it can support, notes it can play are $f = \frac{v}{\lambda} \Rightarrow f_n = n\frac{v}{2L}$ where n = 1,2,3,…



- **Boundary condition – open at one end.** Then again, most wind instruments have a big gaping hole only at one end. So that end's has an *anti-node* of displacement (air moves the most) while the other end has a *node.*
- **Demo: organ pipe with far end closed,** clarinet.

  Now the waves that "fit" are those that have an *odd* integer number of *quarter* wavelengths.

  $L = \frac{\lambda}{4}, 3\frac{\lambda}{4}, \ldots \Rightarrow \lambda_n = \frac{4L}{n}$ and so

  $f = \frac{v}{\lambda} \Rightarrow f_n = n\frac{v}{4L}$ where n = 1,3,5,…

Qualitative Differences. There are two fundamental ramifications of this difference:

- When playing a given note, a tube that's open at one end will also excite all of its harmonics (both even and odd) while a tube open at just one end will excite only half the harmonics (odd) and so sound 'thinner'.
- to play the same note, a tube that's open at both ends must be twice as long as a tube that's open at just one end. Because the one tube need only be as long as a quarter of the sound's wavelength while the other would need to be half the wavelength long. We can see this mathematically

  $$f_{one-end-open} = f_{both-ends-open}$$

  - $$\frac{v}{4L_{one-end-open}} = \frac{v}{2L_{both-ends-open}}$$

  $$L_{both-ends-open} = 2L_{one-end-open}$$

More about resonating air columns in lab next week.

Example: (like homework) *Let's think about that variable-length organ pipe I had; you probably couldn't see, but along one side of the slide were marking indicating how far it should be pulled out to play different notes. Say pulling it out 0.39m allowed me to play A4 (440 Hz); then if I pulled it out 0.44m, what note would it play?

I know that for this organ pipe the fundamental it plays relates to its length via

$$f = \frac{v}{4L}$$

Writing that for both cases,

$$f_A = \frac{v}{4L_A}$$

$$f_? = \frac{v}{4L_?}$$

I can divide the two equations by each other, or equivilantly, solve both for v/4 and then set them equal to each other (since the wave speed will be the same in both scenarios)

$$f_A L_A = \frac{v}{4} = f_? L_? \Rightarrow f_? = f_A \frac{L_A}{L_?} = 440\,Hz\,\frac{0.39\,m}{0.44\,m} = 390\,Hz$$

which, the inside back cover of the book says corresponds to G4 (at least to two significant digits).

- Note: in the end, it we didn't make use of the value of *v* or that it was divided by 4. A similar problem asking about waves on a string of different lengths would have played out exactly the same. Fairly generally for a wind or string instrument, the frequency scales inversely with the length, or, comparing two frequencies and corresponding lengths
    - $f_1 L_1 = f_2 L_2$

Impetus

- While a single pluck sets a string vibrating for a while, a single blow isn't quite so effective, you need a continuous blow, and kind of like the continuous draw of a bow across a spring quickly sets up a stick-slip behavior in synch with the string, the continuous blow gets reshaped into a serious of puffs in synch with the vibrating air.
- **Edge Tone.** One way to get this is with an edge tone - we get this thanks to air turbulence around an edge, say around a reed or the edge in a flute hole or an organ pipe. In some of these cases, the frequencies produced are fairly specific, sounding a little like a duck call – not too musical, but definitely has a basic pitch.
- **Demo –recorder**

Tuning& Amplification

- **Resonance between air column and impetus.** In either case, this air motion contains frequencies in the air column's harmonic series (along with lots of frequencies that aren't in the series). Those frequencies that fit are reinforced as standing waves in the air resonate and grow. Those frequencies of motion are amplified. In some instrument, the pulsing of air that is set-up comes back to the point of impetus (say the buzzing lips on a brass, or the reed on a wood-wind) and reinforce its motion at the right frequencies.
- **Playing.**
    - **Change length.** A trombone is the easiest to consider – you literally lengthen or shorten the resonance tube, thus increasing / decreasing the wavelength and lowering or raising the corresponding pitch.
    - **Change driving frequency.** Another strategy is changing the basic frequency at which your driving the system, say pursing your lips harder – since the column length remains the same, all you can hope to do is jump from driving from one to another resonance – jump octaves.

- **Effectively changing length.** Some instruments have very large holes, and when you uncover them you effectively change the length of the instrument.
- **Select harmonics.** Others have small holes, still, opening them allows their locations to be pressure anti-nodes, and so selects the frequency at which it plays.
- **The bell effect.** Most instruments have a flaired bell at the end, rather than an abrupt stop; one effect of this is that the boundary conditions is a little flexible – there must be an antinode *somewhere* in the bell, but you can push it.