Tu. 2/19: Ch 8 *Spectra and Electronic Synthesis* **Th. 2/21:** Ch 9 *Percussion Instruments*	HW6:Ch8: $1^w,2^w,3,5^w,6$… Ch9: $3,10^w,18^w$, $20,23,25^W$	**Mon. 2/18** or **Tues. 2/19:** Lab 7 *Audio Spectra*
Spring Recess		
Tu. 3/5: Ch 16 *Sound Reproduction* **Th. 3/7:** Ch 16 *Sound Reproduction*	HW7:Ch16:$1^W,7^W,11^W$… Ch16:$13^W,18^W,19^W$	**Mon. 3/3** or **Tues. 3/4:** Lab 8 *Percussion pt 1 - Drums*

Equipment

- Pasco driver, function generator & metal strips (16-24 Hz, 108 Hz)
- Air track with all carts, springs, and adjustable stopper
- Tuning Fork on resonance box (go with tallest thin fork), and fork without box, and mallet
- Strobescope (if fork is 256Hz, set scope to around 25.4 Hz)
- http://www.falstad.com/mathphysics.html
    - LoadedString
    - Coupled masses
    - Flexible bar
    - Circular drum head
- Symbol / pan lid
- Graph paper for everyone
- Masses-on-springs rod
- Masses-on-springs solid
- Matter & Interactions Quicktime of book cover

Administration

- Topics
    - I'll e-mail folks this afternoon to confirm topics.

- **Ch 8 to 9 transition**
    - In chapter 8 we learned how a complex sound wave could be thought of as a combination of pure (sine wave) tones. While the overall repeat frequency of the complex sound determines its pitch, how strongly each component is represented determines its timbre. Like a wine coinsure might try to describe a wine in terms of different 'components' of its flavor – how oaky, how fruity, hint of vanilla,… we can describe the sound of a note in terms of how the different components are mixed, and that's what really distinguishes a flute's version of A_4 from trombone's – same pitch, different timbre, different mix of components.
    - Of course, to produce a complex tone, I *could* set out five speakers with five function generators, each one driving its own speaker head at its own single frequency, and we let all those sounds mix in the air. But that's not how we usually do it; usually, we pick up just one instrument and strum, pluck, blow,… it. Now how does that one instrument simultaneously produce all the pure-tone components of the rich sound? How does it vibrate at all those frequencies at once? That's what Chapter 9 is about – looking at complex motion of an object, a string, a bar, a drum head,… as equivalent to a sum of simple, single-frequency motions: modes.

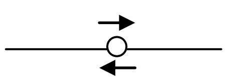
- As we call single-frequency sounds “pure tones”, we call single-frequency vibration of an object a “mode”. These two are, of course, inextricably related.

- **HW.** Before we launch in to all the demonstrations and examples that I hope will help Ch 9 come to life, on a more practical level, I want to work with you on a more practical level – anyone who’s been working on the homework, any questions?

- **Ch 9**
    - In this chapter, we’ll really put Fourier’s ideas to use to understand how a complex sound can be made by complex motion which can be considered a superposition of simple motions.
    - **9.1 Searching for Simplicity**
        - **Demo: Strike “cymbal” (pan lid) & capture wave-form and spectrum.**
            - The oscillations in air pressure / sound wave produced by something like this ‘cymbal’ is quite complicated; in some ways it’s the most complicated of musical sounds thanks to its *non* musicalness. Then again, it’s one of the simplest of instruments – there’s really just one working part, and there’s little subtlety in how it’s played.
        - Looking at percussion instruments in a little more detail will help to firm up our understanding of how, on a fundamental level, complex sounds are produced, and so lay some foundations for thinking of other instruments.
        - **Building from simple understanding in science.** As the book suggests, we’re going to start far simpler than this, and slowly build up. In the spirit of this course’s being an MS1 – for many of you, your taste of a natural science, I should point out that this is an example of a common approach in the sciences, definitely in Physics.
            - Take this marimba bar for example, how well do I understand how it makes sound? I can qualitatively describe it in words, and that’s something; however, in physics, we don’t say we really ‘understand’ something unless we can describe it completely, precisely, and accurately enough to make precise and accurate predictions. Of course, the most precise language we can use to describe something is that of mathematics, so this means we’ve got to be able mathematically describe/model. Until I can write down equations that accurately describe the motion of a marimba bar, equations that I can write into a computer simulation to reproduce its sound, then I don’t ‘fully’ understand it.

- Now, I can't describe the motion of marimba bar *that* well. However, if I examine the marimba bar with my physical-abstraction vision, I see it as a bunch of atoms bound to each other, and when I whack the bar, I'm knocking around those atoms – stretching and compressing their bonds. I know that as long as those bonds aren't stretched or compressed too much, they'll push the atoms back into place just as springs would push masses. Now *that's* something I can mathematically model – a mass on a spring.
- So, I'll build up my understanding of the marimba bar atom by atom – mass & spring by mass & spring.
- In another class, for physics majors, we'd actually do that completely rigorously and, for a simple chain of atoms, we'd end up having derived, among other things, the expression for the wave speed on a string (something you and I have made some use of). In this class, we'll just get a feel for how the logic goes and pull out some of the big points.

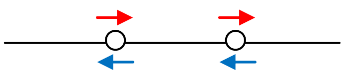
- **9.2,.3 Coupled Pendulums & Natural Modes & their Frequencies**
  - To make sound, something's got to oscillate back and forth. The simplest oscillators we can imagine are a mass swinging from a string or bouncing on a spring. In either case, the mass has just one frequency it likes to move with. We'll see that, as we add on more masses interacting with each other, we get the potential for greater variety of oscillations / greater variety of frequencies of oscillation / greater variety for sounds.
  - We'll follow the book's basic path – start with one mass that can just vibrate back and forth to stretch and compress its spring (longitudinal modes):
  - **Demo:** http://www.falstad.com/mathphysics.html, coupled masses (start with just one mass)
    - **1 mass on 2 springs.**



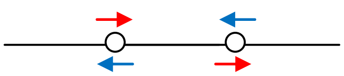
      - If we just have one mass on a spring, it can only move in one way – back and forth, and there's only one possible frequency of its motion, $\frac{1}{2\pi}\sqrt{\frac{k}{m}}$. If we imagine, as is illustrated here, that there are two springs, one on either side, then the mass is subjected to twice as much force for a given displacement, so $f = \frac{1}{2\pi}\sqrt{\frac{2k}{m}}$.
      - As time goes by, the oscillation may slowly decay away, but as long as the mass is oscillating, it's going at *this* frequency.

- **Resulting sound**
  - Imagine we had a very little mass on a very stiff spring, so it was vibrating *very* frequently, say 256 Hz, it would probably be pretty quiet, but the sound waves that it would emit would then have this one frequency.
- **Demo: Air track – 1 cart, 2 springs – 1 mode and frequency**

- **2 masses on 3 springs.**
  - Once you add a second mass, there are a lot more possibilities (pull back one mass and let it go)
  - **Not generally sinusoidal.** Notice how the two masses trade off moving fastest – first one, then the other. In general, when you nudge or pluck this system into motion, neither mass will move smoothly.
  - **Two sinusoidal modes.** But there are *two* ways you could imagine setting going motion to get *smooth* motion



    - **Identical motions**
      - When they're moving identically, then the spring between them never gets stretched or compressed, so it's as good as if that spring weren't there in the first place; then the two masses would clearly be oscillating at $\frac{1}{2\pi}\sqrt{\frac{k}{m}}$



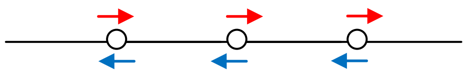
    - **or opposite motions**
      - When they're moving against each other, like mirror images of each other, then the center spring gets *doubly* compressed or *doubly* stretched for a given mass displacement, so, between that and the regularly stretched/compressed springs on the ends, the masses experience 3 times the force, and so have a frequency of $\frac{1}{2\pi}\sqrt{\frac{3k}{m}}$.
    - Notice that in either case, there's a symmetry between what one mass and the other mass is doing – if one mass is speeding up because the springs by it are particularly stressed, well so is the other

mass – so the motion *is* smooth and sinusoidal.

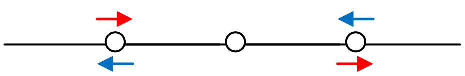
- **Demo: Air track – 2 carts, 3 springs – 2 modes and frequencies**
- **General**
    - Now let's pluck one mass again and compare it's motion to the two simple motions
    - While the actual motion looks pretty complicated compared to just standing still,
    - **Mode 2 *about* Mode 1**(highlight the in-synch mode) if we compare it against, say the simple in-synch mode, then it looks a lot simpler – like the masses are oscillating as mirror images (second mode) about where they'd be if they were in-synch (1st mode).
    - **Mode 2 + Mode 1.** Put another way (click the "stop" button and then highlight one and then the other mode), the actual motion is simply a *sum* of the two simple motions.
    - *Any* motion that these two can execute, can be seen as such a combination of the two modes, it's just a matter of the relative amplitudes. (vary relative amplitudes for different motions)
- **Fourier**
    - That notion should sound awfully familiar – complex oscillation is the sum of simple oscillations; all we need to specify is the frequency and amplitude of each simple oscillation, a.k.a. "mode" – that's the spectrum.
- **Sound Produced**
    - Again, imagining these as little masses on stiff enough springs that they vibrated at audible frequencies – if in one or the other simple mode, then we'd here just one or the other simple pitch, but more generally, we'd here a complex sound composed of the two mode's frequencies of different relative amplitudes.

- **3 masses on 4 springs**
    - The same could be said for a system of 3 masses, but now, rather than having just two simple modes, there are three. Again, the simple modal motion is that which *is* of constant frequency.

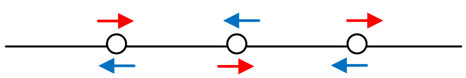
- **Show three modes, and then pluck and push to get more general motion.**



  - **1: Move left and right together.**
    - Note; this mode is similar to the one that the book shows for three pendulums connected by springs, but it differs in that the motion is purely caused by the *springs* (as opposed to relying on a pendulum's own tendency to swing), so the only way the central mass will move back and forth is if the springs beside it get compressed and stretched – still, it moves left and right in synch with the other two, just with larger amplitude.

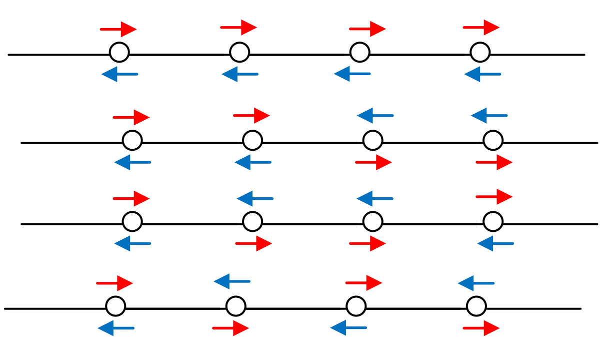


  - **2:** the outer ones move against each other – so the middle one's caught in a tug-of-war and goes nowhere.



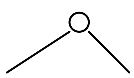
  - **3**: every-other one moves opposite its neighbor (zig-zag mode)
- **Demo: Air track – 3 carts, 4 springs – 3 modes and frequencies** (going to need an assistant for a 3^{rd} hand)
  - **General:** Again, any motion that these three masses can execute can be seen as a combination of these three modes
    - **show** the 1^{st} and 2^{nd} mode exited, track motion of the 1^{st} and see motion relative to that
    - **show** a combo of all three.

- **4 masses on 5 springs**
  - **(before moving the slider to have 4 masses) Question: How many modes will this system have?**
    - **4**
  - **Who has an idea what one of them might look like?**

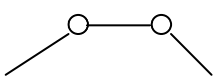


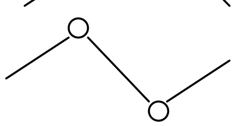
    - **All moving in synch** (central two have greater amplitude, but do not compress central spring)
    - **Left 2 move against Right 2**
    - **2 outers move against 2 inners**
    - **Each moves against its neighbor.**
  - **Generally.** The general possibilities are still richer, but they're made up of combinations of these four modes with different amplitudes.

        - **Demo: Air track – 4 carts, 5 springs – 4 modes and frequencies** (going to need an assistant for a 3rd hand)
        -
    - **N masses on N + 1 springs**
        - **There would be N simple modes**
        - **General motion**
            - would be like a combination of each of these with different relative amplitudes.
        - **Sound Produced**
            - Would sound like all these frequencies with their relative amplitudes.
- **Transverse modes.**
    - Now, what if the masses, rather than being confined to move toward and away from each other, they were confined to swing by each other?, so rather than stretching and compressing the springs they 'plucked' them like this?

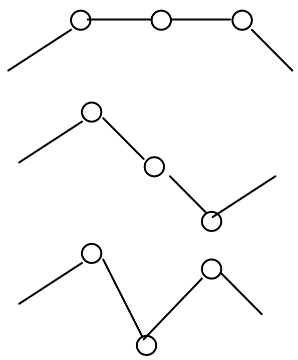


    - **1 mass on 2 springs** (loaded string with 1 mass)Coupled masses applet.
        - Again, there's just one kind of motion with one frequency of oscillation,
        - **Sound:** and therefore, one pitch of sound produced (turn on sound, then turn back off)
    - **2 mass on 3 springs**
        - How many simple modes? 2





            - **Mode 1**: Move together, with one constant frequency
            - **Mode 2**: Move opposite, with another constant frequency
        - **Generally**
            - Any motion that can be executed can be seen as a combination of these two
                - set combined motion going and hilight fundamental so they can see combo as motion relative to fundamental
                - Stop motion and select one and then the other mode to see that combination is simply the sum.
        - **Sound**
            - The sound of any combination would be like the simultaneous sounds of the two individual modes. (turn on sound)



- **3 masses on 4 springs**
    - **3 modes**
        - **1** All move together
        - **2** Ends move opposite and center stationary
        - **3** Each moves opposite its neighbor (zig-zag)
        - **Note:** These are the same kinds of modes as for three masses moving toward and away from each other
    - **General**
        - General motions are all combinations of these three of different amplitudes
        - **Demo**: Turn on 1st and 3rd harmonics and see combined motion as 3rds oscillations about 1st.
    - **Sound**
        - The sound produced by a system oscillating like this would be combinations of these three mode's sounds (turn on sound for general motion)
- **5 masses on 6 springs**
    - The book shows these 5 modes
- **N masses on N+1 springs**
    - There are N modes of oscillation for this virtually continuous string.

- **3-D motion**
    - Most generally, an individual mass bound by springs can move left-right, front-back, and up-down, so in 3 discrete directions in 3-dimensional space. So, if you have a combination of N masses, then there are 3N modes (N left-right, another N front-back, and another N up-down).
- **Balls-on-springs model of solid**
    - That's important because, any chunk of material is like a bunch of masses connected by springs / atoms connected by bonds.
    - **Movie of masses on springs.** So we could generalize what we've seen of chains of masses to this – the most complicated of motions can be thought of as a sum of simultaneous simple modes of motion.
- **The Main Points**
    - Every system of point masses (be it a string on a guitar, or a cymbal) has some number of different modes of oscillation which scales with the number of masses.
    - Each mode has all parts of the system executing simple harmonic motion in unison, with the same frequency.

  - All complex vibrations of the system can be resolved (Fourier-like) into a combination of these modes, each with specific amplitudes (thus, a specific spectrum).

- **9.4 Tuning Forks and Xylophone bars (**Flexible bar applet)
- In some ways, we've used these basic ideas already in this class – when we identified the nearly infinite family of standing wave modes that a string or column of air (with its virtually infinite number of atoms) can support, and with our insistence last chapter / Tuesday that we could describe any complex tone in terms of simple pure tones (modes) of specific frequencies and amplitudes – a specific spectrum. But now we're going to be more specific about using this conceptual model.
- **Tuning Fork**
  - A tuning fork is two connected solid beams, each one of which can be thought of as a series of masses connected by springs (atoms connected by bonds), so there will be a series of possible modes of oscillation. Given that one end is essentially fixed and the other is free, the simplest you might imagine would be
    - **Demo**: BarWaves applet (set ends clamped/free)
    - **Demo**: Pasco driver with resonance bars – longest resonates around 16 Hz.
  - This is indeed the dominant mode
    - **Demo:** Tuning Fork with strobe light (fork around 256Hz, light around 25.4Hz, with blinds closed)
      - I'm pretty sure those of you nearby can see the fork's tines moving a few millimeters left and right, hopefully some of the rest of you can too.
  - **Higher Frequency Modes** While that's the easiest mode to excite, it isn't the only one; in fact, when I strike the fork, especially one not anchored to a resonance box, you hear a much higher pitch too
    - **Demo: 2^{nd} mode in simulation (the "clang" tone)**
    - **Demo:** Pasco Driver with bars – longest's 2^{nd} mode around 108 Hz
      - **Frequency/Sound:** Note that this 2^{nd} mode isn't just twice or even three times, but about *6* times higher than the first mode. This is a real difference between a string, or even air, and a stiff bar
        - $f_n \approx \left[2.81\left(n-\tfrac{1}{2}\right)^2\right]\left(0.162a/L^2\right)\sqrt{Y/D}$ where a is the cross-sectional area, L is the length, Y is young's modulus, and D is the density. (but the fundamental is with the term in square brackets = 1)

        - **Combination -** Highlight 1st mode while both are running, so combination can be seen as 2nd mode oscillating about first.
        - **Demo:** Play sound with 1st and 2nd mode. This sound is hopefully familiar from striking the tuning fork.
    - **Still higher modes.** Since there are umpteen atoms, there really are umpteen modes, but under normal conditions, the bottom two dominate
        - **Show higher modes.**
- **Xylophone bars**
    - There's a whole family of percussion instruments that are based on a free bar that is struck with a mallet – having slightly different boundary conditions (both ends are free), the relation between the different modes is slightly different from that for the bar fixed at one end
        - $f_n \approx \left[0.441\left(n+\tfrac{1}{2}\right)^2\right]\left(0.028a/L^2\right)\sqrt{Y/D}$ (with the fundamental having the term in square brackets equal to 1).
        - **Demo:** BarWaves applet with free ends.
            - First play the sound of just one and then another mode
            - Then turn off the 'sound', turn off damping, dial up 1st, 2nd, and maybe 5th mode and then "sound" to hear something much like a xylophone bar.
    - **Shaping and resonating**
        - Unfortunately, these non-integer relations between the modes means that when they sound simultenously, they do *not* produce a pleasing steady tone since they do not have an over-all repeat frequency. The instrument can be made more 'musical' by carving out the center of the bar so that the lowest mode, which must bend only there, finds the bar much less stiff, and so its frequency is lower – the right amount of carving can get the fundamental down to 3 or 4 times the 2nd mode, so they are truly harmonics – combining to produce a steady 'musical' tone. For the marimba the bar is thinned to make the fundamental ¼ the 2nd mode, and for the xylophone its only thinned to be 1/3. (Higher frequency modes aren't strong enough or long-lived enough to worry about matching.)
- **9.5 Drums, Cymbals, and bells**
    - Won't get into too much detail, Patrick will be talking about a specific drum, but want to touch on the basic modal patterns. These are really 2-D generalizations of the 1-D patterns for bars and strings.
        - **Demo:** Drum Head app. (2D+3D view, mouse set to strike drum)
            - Step through some modes

- Strike in center (what modes do you predict will get excited?)
- Strike off to a side.

- **9.6 Striking Points and Vibration Recipes**
  - The modes that are going to be most strongly excited when you strike the object are those that want the medium to move the most right where you struck it / the modes that are weakest are those that want the medium to *not* move right where you struck it.
    - **Demo:** Drum Head app. (2D+3D view, mouse set to strike drum)
      - Strike in center (what modes do you predict will get excited?)
      - Strike off to a side.

  - The larger space over which you strike (as with a fat mallet), the more 'pie wedges' you over lap, and so shorter-pattern / higher frequency modes are reduced.
  - The initial strike of the stick or mallet sets the membrane vibrating, if the mallet *remains* touching the surface, then acts to *adsorb* the rippling and dampen vibrations.
- **9.7 Damped Vibrations**
  - Those modes that more efficiently transfer energy out, dampen fastest – maybe that's because they move the most air, maybe that's because they want to move the object right where something's restricting their motion. In any event, that means that a complex sound doesn't just uniformly grow quieter – its 'color' changes as it goes – maybe it "brightens" with the low frequencies dying out first, or may be it "darkens" with the high frequencies dying out fastest.