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)

Materials

- Tunning Fork with adjustable mass attachments, resonance box, mallet
- Torsion Wave machine including end clamp
- string ‘instrument’
    - mallet, pick, violin bow
- elastic string , pulley, Pasco function generator and driver – for string wave demo
- PhET wave-on-a-string (turn damping off)
- Fourier Synthesis box and o’scope and laptop (and USB cable and two BNC cables) (show superposition)
- Speaker and cables to plug into Fourier Synthesis box
- Projector and wave tank and beam for tapping water
- Music box
- Violin back for PASCO, sand (and box for collecting sand)
- Clickers on side table (plug in receiver)

Add examples like problem 3 and 7 – what frequency is how many octaves above/below a given frequency and if an instrument of a givne length plays the one, then what length is needed for the other?

Setup

Turn on computer and bring up black-out ppt.

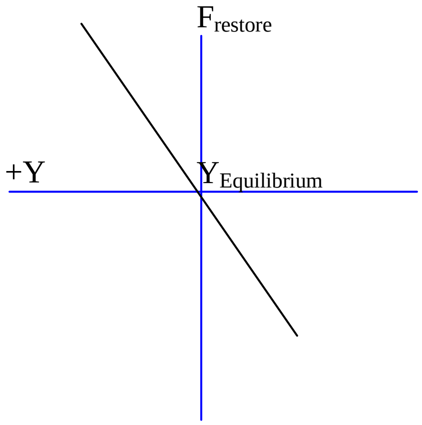
Intro.

As you’ve probably noticed form the book’s index, these early chapters give a quick, and rather superficial overview of the main themes of musical acoustics, then the later chapters return to each of the themes in turn and in greater detail. For example, this chapter gives a quick overview of sound *production* by musical instruments; later chapters focus on percussion, string, and wind instruments. I’m avoiding covering those chapters myself because I imagine that many of you will be interested I hitting on much of that content when it comes time for presentations near the end of the semester, and I don’t want to steal your thunder. Still, Ch. 3’s a little too superficial to stand on its own until then, so, I’m going to cover musical sound production in *a little greater* detail than Ch. 3, but still leave plenty for you for later.

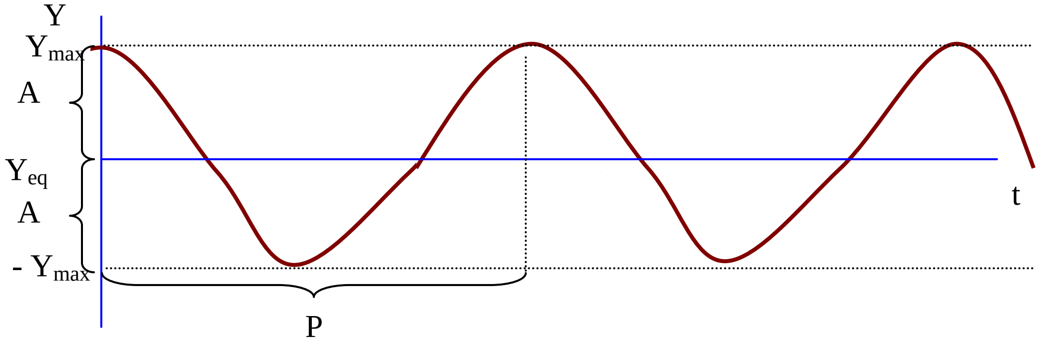
Last Time

2.4 Simple Harmonic Oscillation (SHO)

- Not only is this type of motion fundamental to waves, it underlies the vibrations of all matter, and thus is fundamental to every step of the sound process: production, propagation, and even perception.
- **SHO: Necessary Conditions.**



  - A) **Equilibrium Position**
  - B) **Restoring Force**
    - **restoring force must be linearly proportional to the displacement** from equilibrium.
  - D) **Inertia**
    - **Law of Classical Mechanics:** A body's motion is only changed through an interaction. Newton's version: A body in motion tends to stay in motion unless acted upon by a force.
  - **Clicker Question:**
    - I'm going to attach these masses to the prongs, will the pitch be
      - A) Higher
      - B) Unchanged (though the loudness is changed)
      - C) Lower
      - D) I really don't know
- **SHO: The process**
  - |F| = k Δy.



Mathematically, the functional form is $Y(t) = Y_{\max}\cos\left(2\pi\frac{t}{P}\right)$

- **Moral**
  - Simple Harmonic Oscillation results from two competing influences on a body's motion: a restoring force that pulls it toward equilibrium, and inertial which makes the body overshoot equilibrium.

- **Mass on Spring: Dependence of P on force and inertia**
  - $P = 2\pi\sqrt{\frac{m}{k}}$, or the frequency is $f = \frac{1}{P} = 2\pi\sqrt{\frac{k}{m}}$

- **Pendulum**
    - We can see the same basic behavior in a pendulum
        - $P = 2\pi\sqrt{\frac{L}{g}}$
- **Tuning Forks**
    - A simple harmonic oscillator from music that is much like the pendulum & the mass on a spring. The two arms of the fork oscillate back and forth like the pendulum, and the frequency with which they do so depends on their stiffness & mass (distribution).
    - **Demo: tuning forks**

Waves

- **SHO -> Waves**
    - The coherent motion of a medium full of Simple Harmonic Oscillators is a wave.
- **Wave Speed on String Similar to Simple Harmonic motion**
    - Like a simple harmonic oscillator, for a wave being transmitted down a string, how quickly the motion occurs depends upon how strongly bound the pieces are and how massive:
        - $v = \sqrt{\frac{F}{M / L}}$
    - Same basic dependence, bigger force, faster, bigger mass (inertia) slower.

Powerful Concept

- **Simple Harmonic Oscillation** is an extremely powerful concept because
    - So many things around us execute it (or approximately it)
    - Even when motion is much more complicated than this, that complicated motion can be described in terms of simultaneous simple harmonic oscillations of different frequencies.
    - You're ear actually resolves complicated air motions, i.e. sounds, into individual, simultaneous simple harmonic oscillations

2.5 Work, Energy, and Resonance

- **Resonance in instruments**
    - Amplifies
    - Selects specific frequency from driving forces

This Time

Chapter 3 Sources of Sound

Introduction: The common elements

- We will see that 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.

There is little mystery to the first step, and the third step will be simple enough to understand once we look at it. The second step is where the magic of music occurs. Selecting out of a 'noisy' input (say a pluck) the simple, harmonic tones. The underlying mechanism is **resonance** and the formation of **standing waves**.

Resonance:

A simple harmonic oscillator has a natural frequency of oscillation. This frequency is determined by the strength of the restoring force bringing it toward equilibrium and the inertia that carries it through equilibrium.

A wave is the coherent motion of coupled simple harmonic oscillators. The speed with which the oscillation translates through the medium depends again on the interplay of a restoring force and the inertia. For a wave in a string: $v = \sqrt{\frac{T}{\mu}}$. This speed has absolutely nothing to do with how the string is plucked.

We are ultimately interested in pitch or the frequency of something's motion, so how is this related to the frequency?

$$v = f\lambda,$$

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

In most musical instruments we'll see that by controlling the length of the resonating element, be it a column of air or a string, we control the wavelength. This determines the frequency, and thus the pitch.

$$f = \frac{1}{\lambda}\sqrt{\frac{T}{\mu}}$$

3.1 Classifying Sound Sources

- **Natural vs. Artificial**: Here the author means to distinguish between a sound found in nature, like a bird chirp, and a sound produced by an instrument specifically designed or manipulated for 'music' (though he notes this is a problematic distinction.)
- **Original vs. Reproduced**: We will spend some time discussing original but make much use of reproduced for dissecting it and the natural step after dissecting an original sound is reconstructing it synthetically. We will look at synthesis.
- **Transient vs. steady**: For some instruments, the impetus comes as a discrete motion: a pluck or strike. The tones they produce are dominated by the 'attack' and 'decay'. For other instruments the impetus is continuous motion, a bowing or a blow. These produce sustained notes tones.
- **Percussion vs. String vs. Wind**

3.3 String Instruments

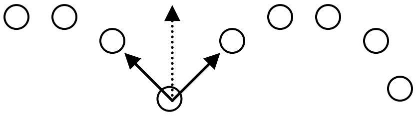
- We'll start here because it is the simplest to visualize;
- Let's home in on the string first and really develop an understanding of how a string can resonate and select our pitch.

- I'll be drawing from both Ch 3 and 10.1 and 7.4 (which you'll want to read for the lab)

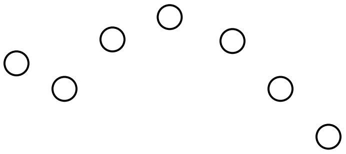
- **Introduction:** We introduced the idea of simple harmonic motion and we investigated some of its properties – amplitude, repetition in time. We then expanded upon the theme of vibration to waves. Sometimes it was convenient to focus on just one pulse, or wave front moving through the medium, to see how the medium's properties influenced the propagation. Sometimes we looked at a full-blown wave – with its repetition in time and throughout the medium. All the time, we kept the wave simple – sinusoidal, and in isolation. Now look at how two individual waves coexisting in a medium – in the same space, at the same time, combine, or interfere, to produce complex patterns of distortion through the medium.

The Principle of Linear Superposition

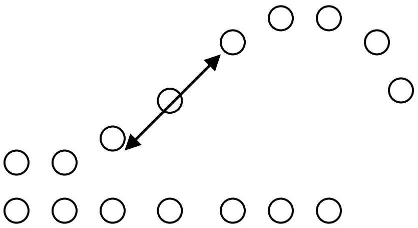
- When we first began talking about waves, we looked at just one pulse, or wave-front propagating through the medium. To begin talking about the interaction of waves, we'll first look at how two lone wave pulses interact.
- **Demo: two pulses on the torsion wave demo.**
    - First do just one pulse to a stationary end and note how it is reflected from that end
    - Then do one pulse after another, see where the 2nd interacts with the first one's reflection.
    - Do ones where they meet both up & where the meet one up & one down.
- **Individual particle picture of equal pulses meeting.** Look at it on the individual beam level & think about how the two waves interact.
    - **Demo: PhET waves-on-a-string** (by hand, one pulse up, and then one pulse down so when the reflection of the first meets the second they *constructively* interfere)
    - **Pulses in same direction**



        - **Pulse from left:** Say there's a pulse coming from the left. On its leading edge, each beam pulls up on the one to its right, on the trailing edge, each beam pulls down on the on to its right.
        - **Pulse from right:** Now there's a pulse coming from the right. On its leading edge, each beam pulls up on the one to its left, and on the trailing edge, each beam pulls down on the one to its left.
        - **The two pulses meet**. When the leading edges meet, the beam in the middle feels twice the pull up – one from the left and one from the right. So it rises extra far.
        - **Constructive interference:** Pulses (or full waves) interact to produce even larger distortion in the medium.



    - **Pulses in opposite direction**
    - **Demo: PhET waves-on-a-string** (use "pulse" setting to send one and then another pulse from the left so that when the second meets the reflection of the first, they *destructively* interfere.)

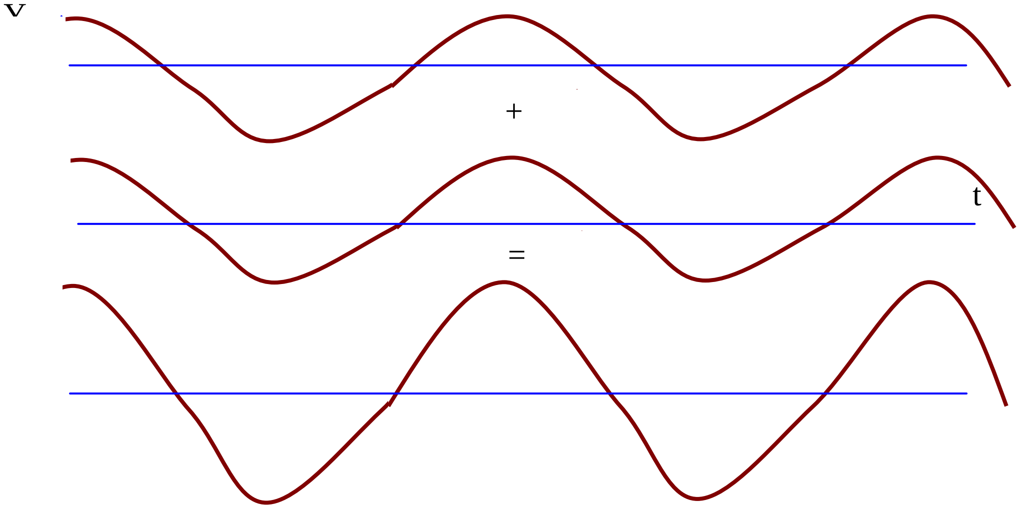


- **Pulse from left:** the leading front is of a beam pulling down on its neighbor to the right.
- **Pulse from the right:** the leading front is of a beam pulling up on its neighbor to the left.
- **The two beams meet.** In the middle is a beam that is getting pulled up from one side, but pulled down from the other – it goes nowhere.
- **Destructive interference:** Pulses (or full waves) interact to produce even smaller distortion in the medium.

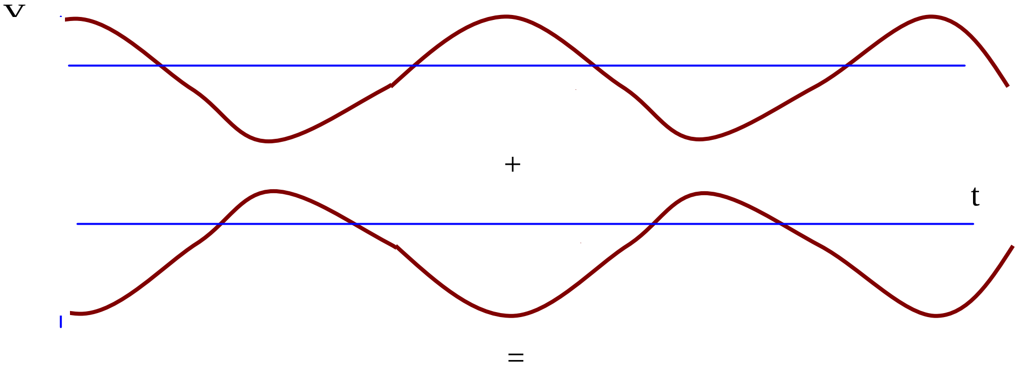
- The guiding principle here is
  - **the Principle of Linear Superposition**: When two or more waves are present simultaneously at the same place, the resultant disturbance is the sum of the disturbances from the individual waves.
  - This is true of sound, water, and even light waves.

Constructive and Destructive Interference of Sound Waves

- Expanding from a picture of just individual pulses to whole waves interacting, the simplest case of Constructive interference is of waves of the same frequency being perfectly in synch, or *In Phase*, everywhere in space. These two would add to make a larger wave everywhere.
- **Demo: O'scope looking at same**



- The simplest case of Destructive interference is two identical waves perfectly *Out of Phase*, i.e. when and where one is maximum up, the other is maximum down. These two would add to completely cancel.



- **Full Waves 1-D propagation**
  - Now consider a series of pulses, a wave, running to the left
  - **Demo: torsion wave driven at open end**
  - Then a series of waves running to the right
  - **Demo: drive from dampened end and clamp the other stationary**
  - The two combine to make a pattern of
    - **Nodes:** points where they completely destructively interfere – no distortion,
    - and
    - **Anti-nodes:** points where they maximally constructively interfere – most distortion.
- **Most General superposition:** More generally, two very different waves are simultaneously driven through the same medium, and the result is simply their sum:
  - **Demo: Fourier Synthesis device – add in a few different harmonics**
    - See on o'scope
    - Play over speaker – intriguingly, while the plot on the scope shows the complicated addition of the different oscillations that are together propagating through the air to your ear, when they get there, your ear separates them out again into distinct tones – more about that when we get to the chapter on the ear.
- **Standing Waves**
  - Now, something very special happens when two identical waves traveling in opposite directions meet, for example when a wave and its own reflection meet.
  - **Demo: standing wave on torsion beam**
  - The wave and its reflection add to create a stationary pattern of **Nodes** and **anti-nodes**. This is termed a standing wave.
  - Though the pattern isn't going anywhere, we can still think of it as the addition of two traveling waves, so while 'wave speed' may not seem a useful concept, the relationship still holds. For a string we still have the wavelength and frequency related by
    - $f\lambda = v = \sqrt{\frac{T}{\mu}}$
  - **Wavelengths Determined**

  - So, how does this select out the frequency?
    - Look at the wavelength. The only standing waves that a string, bound at both ends, can support, must satisfy the condition that it not be moving at either end, i.e., that there be nodes at both ends. What wavelengths satisfy that?
  - **Demo:**
    - Driven string. First dial in fundamental
      - L = ½ λ
    - Q: What other patterns can it support?
      - L = λ
      - L = 3/2 λ
      - …
      - L = n/2 λ, n = 1,2,3... or λ = 2L/n
  - **Frequencies**
    - $f\lambda = v = \sqrt{\frac{T}{\mu}}$
    - $f = \frac{1}{\lambda}\sqrt{\frac{T}{\mu}}$
 $f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}$, n = 1, 2, 3,…
  - **Fundamental** = The longest wavelength, the lowest frequency, just one hump, n = 1
  - **Harmonics** = The shorter wavelengths, higher frequencies; n =2, 3, 4,…
    - **Ex.** 4th Harmonic is n = 4, $f_4 = \frac{4}{2L}\sqrt{\frac{T}{\mu}}$
  - **Octave** – A bit of vocabulary: in music-speak, when you double / cut in half the frequency, you increase/decrease the pitch by an "octave." Looking at the back of the book, you'll see that each octave step repeats the note name: A4 is 440Hz, A5 is 880Hz, A6 is 1760Hz… This speaks to just how strongly we identify a note and it second harmonic with each other.
  - **Multiple strings on an instrument**
    - Of course your typical stringed instrument has not just one string, but several. By varying in density and tension, their wave speeds are varied, thus their frequencies are varied.
    - You tune by adjusting the tension – wave-speed.
  - **Demo:** two different strings on 'guitar', different tensions – different frequencies.

- **Impetus**
  - So now we've seen how a string moves, with what frequencies it likes to move. Of course, to set things in motion, you pluck, bow, strike the string.

Say one plucks the string. The plucking itself isn't particularly musical; it doesn't have any particular frequency. Equivalently, it can excite all frequencies (at least those that don't have nodes where you pluck it.) The string responds to the frequencies that fit and not the rest. So it moves at its fundamental and its higher harmonics at the same time. It doesn't respond to any of the other frequencies in the pluck.

- **Demo: Fourier synthesis of triangle Wave. (1, -1/9, 1/25, -1/49)**
- **Q:** With a stringed instrument, how do you vary the sound it produces?
  - **Finger placement**
    - Firmly pressing on the string effectively shortens it, change the length, L, and thus the frequency
      - $f_n = \frac{n}{2\mathbf{L}}\sqrt{\frac{T}{\mu}}$
    - **Example (clicker):** If plucking a 1/2-meter long open string plays A_3 (220Hz), then how short must you make the same string (by placing your finger on the frets) to play E_5 (660Hz)?
      - A) 1/3 meter
      - **B) 1/6 meter**
      - C) ½ meter
      - D) ¼ meter
      - E) I don't know
    - Lightly placing your finger on the string dampens out harmonics without nodes where your finger is.
  - **Tuning**
    - You tighten the string – vary the force of tension, T
      - $f_n = \frac{n}{2L}\sqrt{\frac{\mathbf{T}}{\mu}}$
  - **Different strings**
    - The different strings are anchored at different lengths, L, and may be of different thickness, thus more mass per length., $\mu=(M/L)$
      - $f_n = \frac{n}{2L}\sqrt{\frac{T}{\boldsymbol{\mu}}}$
  - **Plucking vs. Striking**
    - Plucking the string makes the contact very brief & thus allows the high frequency vibrations to survive. So the timbre is composed of a broad spectrum of the harmonics – high and low. The high frequency contributes 'brightness' to the sound.

            - Striking generally has the hammer remain in contact longer than would a pick, this longer contact dampens out some of the faster, higher frequency, vibrations. So the timbre is composed mostly of the lower harmonics – lower frequencies, and a 'darker / warmer' sound
        - **Bowing** (demo note: lightly draw the bow perpendicularly across the string)
            - When the bow is dragged across the string, the string catches on it and is pulled side-ways, then the string slips back toward being straight, but catches again. This stick-slip motion gives a driving frequency at the fundamental & so emphasizes it, warming the sound.
- **Next 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've heard (or rather not heard) no sound get's transmitted. So it's not just how much the object 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 tap water with just a post on the Pasco driver
                - Then tap 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 popular 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 translates into the front plate (and through a post in violins, the back plate) vibrating.
        - **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:**
        - 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.

3.2 Percussion Instruments & wind & brass