Tu. 1/15: Ch 2 *Waves and Vibrations* **Th. 1/17:** Ch 2 *Waves and Vibrations*	HW2: Ch2: 1^w, 13^w, 20^w, Project 1 Ch2: 12, 24	**Mon. 1/14** or **Tues. 1/15:** Lab 2 *Harmonic Motion*

Prep
- Log on & fire up projector (ppt black-out)
- Turn on o'scope and then, after it's fully on, plug into computer
- Go to pHET and open Masses on Springs (http://phet.colorado.edu/en/simulation/mass-spring-lab)
- Make sure

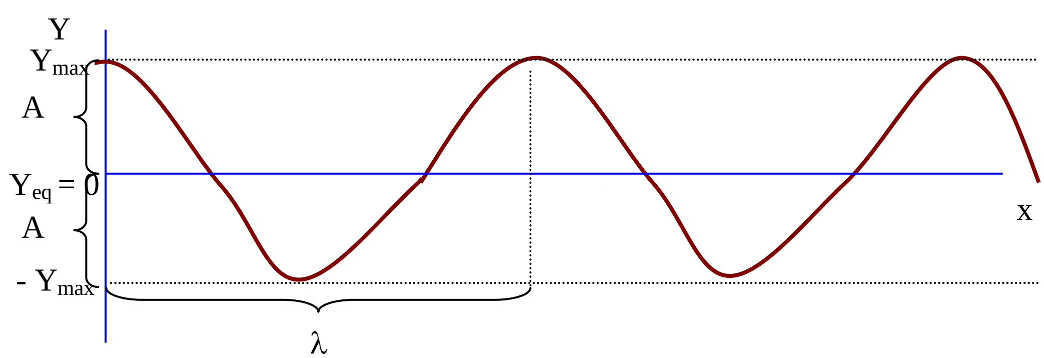
Materials
- Lab 3 handout
- Torsion Wave machine
- VPython's mass on spring with energy.py (put on network drive)
- Lab set-up
  - Oscilloscope – laptop, USB cable, power cable
  - Microphone
  - Function generator (can be same as for driving Pasco driver)
- Speaker
- Mass set and two different springs, also two springs as used in lab
- Driver with connector to pull down on spring
- Beams from which to hang mass and spring
- Tuning forks
- Tuning fork with movable mass
- Tuning fork resonance box.
- Air track, 2 carts of different masses, air track air supply
- Mass-spring model of solid and rod
- Mass on string for pendulum (adjustable length)
- Thumb drive with VPython mass on spring with energy plots (for laptop since instructor machine always gets VPython wiped)

This Time

We will consider what the 'simplest' functional dependence on position and time is for sound. It is so simple and ubiquitous that it has a name of its own: **simple harmonic oscillation.**

<u>2.4 Simple Harmonic Oscillation (SHO)</u>

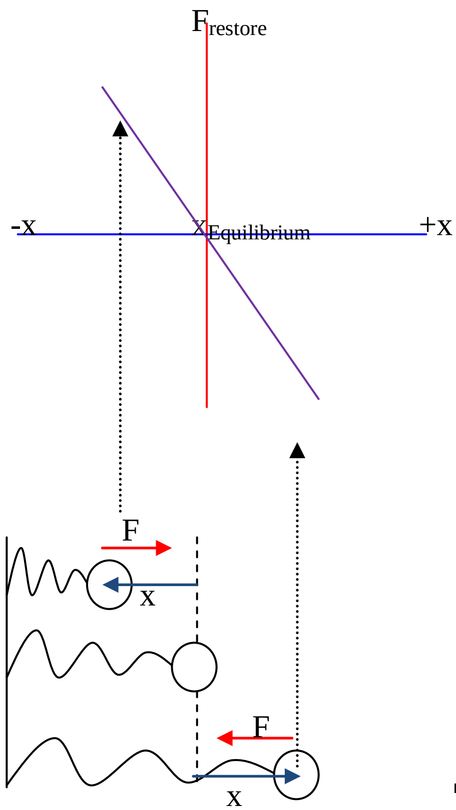
- **Introduction:** Having identified the propagation of sound as a wave phenomenon, last time we talked about some of the fundamental properties of waves: the amplitude, and the wave's repetition through space, every wavelength, and through time, every period.



- **Frequency, wavelength, wave-speed relationship.**
  $v = f\,\lambda$.

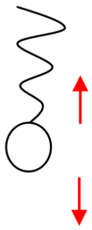
Demo: torsion wave machine

- We looked at and listened to sounds of different waveforms – coughs, hums, whistles, and observed that the purer the tone, the more it looked like a simple sine wave.
- This kind of motion gets a name of its own – **simple harmonic oscillation**. 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. It is therefore well worth our pausing to focus of Simple Harmonic Oscillation.
- **SHO: Key Elements.**
  - In the most general terms, an object executes simple harmonic motion if
    - A) It has an Equilibrium position at which it would naturally rest.
      - **Equilibrium**: not being pulled or pushed at all, or, having all your pulls and pushes cancel. No Net Force acting on the body.
        - Ex. Your body, sitting in your chair is in a state of equilibrium. The mass in the Earth beneath you is pulling you down, but the chair is holding you up. These two forces cancel, leaving you unaffected.
        - Note: to be in equilibrium **doesn't mean not moving** – just **not experiencing any forces**, for example, a hockey puck glides along with nearly no net force, so it's nearly in equilibrium by this definition
    - **B**) If it is slightly disturbed form equilibrium, there must be a lone, or combined, pull / push (force) that tends to restore it to the equilibrium position. Such a force (or combination) is called a **Restoring Force.**
      - Example: If, as you played with in lab yesterday, a **mass hanging from a spring** is pulled down, the spring pulls the mass back up.
      - Example: a **marble rolled up the side of a bowl**, gravitational attraction to the Earth pulls it down, and the walls of the bowl confine it, so it moves back toward the bottom of the bowl.
      - Example: If an **atom of, say the table**, is pushed slightly out of place, its chemical bonds to its neighbors pull it back.
      - Example: If **air molecules** gather in a crowd of higher density, the added intermolecular collisions drive them apart again. Note the qualitative difference – it's not a question of whether any one specific air particle gets out of place, but whether the density of air is uneven.

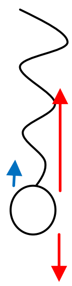


- C) To be strictly SHO, in the well-defined mathematical sense, the **restoring force must be linearly proportional to the displacement** from equilibrium. So if the mass on a spring is moved twice as far out, then the spring pulls twice as hard to move it back toward equilibrium.
  - **Small displacements gives linear relation**: In truth, most real restoring forces *aren't iperfectly linear* however, for small displacements, they're as good as. Some of you had the opportunity in lab last week to observe that if you zoomed in on the oscilloscope's plot *enough* all you saw was a straight line – the sound being plotted by the scope could vary rather jaggedly with time, but if you zoomed in enough, all you saw was the straight line.
    - **Demo –** play square wave over speaker into microphone and zoom in and in and in until linear.
  - The same could be said for a plot of restoring force vs. displacement – if you zoom in enough / are only concerned with very small displacements, then regardless of how complicated the relation may really be, all you see is a straight line. **Moral**: most any restoring force *is* linearly proportional to the displacement if the displacement is *small* enough.
- D) **Inertia** = the tendency to keep doing what you're already doing, in terms of motion, keep moving with the same speed and in the same direction. In the *total absence* of external force, we imagine something would just keep going forever.
- **Demo: Carts on air track**
  - The cart moves from one end to the other and hardly slows in the process – if there were *not* drag, it wouldn't slow at all.
- In the *presence* of an external force, how hard it is to make an object change its state of motion depends on its **Mass.** For example, if a ball rolls out into the road and a car hits it, the car's motion hardly changes, but the ball gets launched.
  - **Demo: Massive one hits light one.** A little less dramatic, this big cart's motion doesn't change as much as does this small cart's.

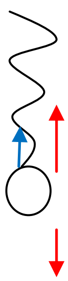
- **SHO: The process**
  - We'll use a **mass on a spring** as our main example, but a real one moves too quickly for me to talk through the process, so let's watch one of the simulated one slowed down.
  - **Demo: set the mass bobbing in PhET Masses on Springs.**



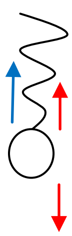
  - Just hanging, the mass is being pulled up by the spring and down by its gravitational attraction to the Earth.
    - This pull is known as its **weight** – the gravitational interaction that underlies this force depends on the object's mass, the Earth's mass, and the nearness of the two. For objects near the surface of the earth, like you, me, a ball, a bird,… the strength of that pull is approximately
      - $w = mg = m*(9.8m/s^2)$ as you used in lab yesterday



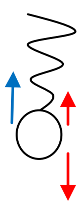
  - Remove either of these two interactions, and the object would go flying in the opposite direction. Together the two pulls hold the object in balance: in **Equilibrium**.
  - Now I pull the object down and let go. The attraction to the Earth is essentially unchanged; however, the spring pulls harder back up; in fact, its pull up scales with the displacement down:
    - $|F| = k\,\Delta y$.
      - The constant is referred to rather generically as the "spring constant", but a little more informatively, we can call it the spring's *stiffness*. So when we talk about 'stiffness' in this class (or in the homework), we mean something very *specific* – the restoring force per displacement.



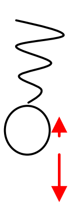
    - So now it out strips the gravitational pull down.
  - **Below equilibrium: pull up / accelerate up.** Due to this net pull up, the object starts moving up. At first it moves slowly, then faster and faster (as long as there is a net force on an object, the object will accelerate) until it arrives back at its equilibrium position.



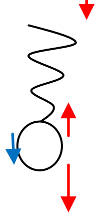
  - **At equilibrium: no pull / no acceleration / continued motion up.** However, it can't come to a dead halt the instant it reaches its equilibrium. In fact, due to its property of inertia, quantified in its mass, it is happy to just continue sailing upward right through equilibrium.



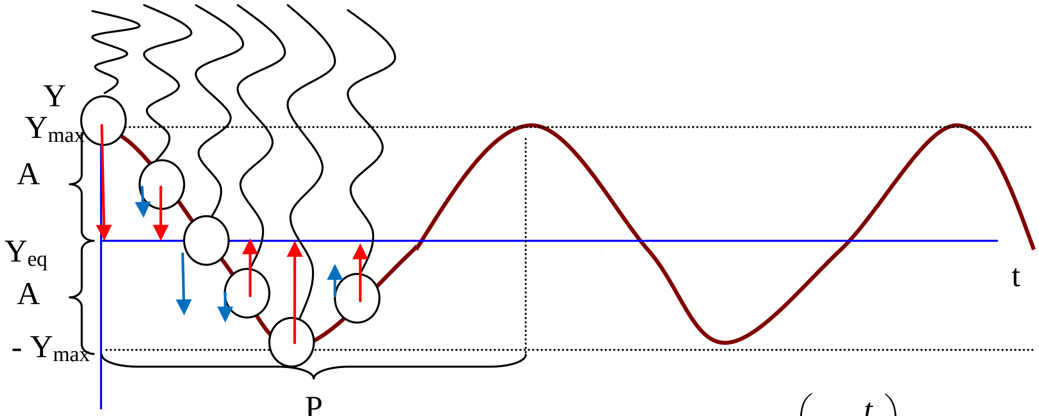
  - **Above equilibrium & headed up: pull down / accelerate down / slow rise.** Now the spring force up is less than the gravitational force down, so there is a net pull on the object down.



  - **At peak & stopped: pull down / accelerate down / momentarily halt.** Due to this, it slows and slows until it comes to a halt and begins to fall.



  - **Above equilibrium & headed down.** Again it speeds until it reaches the equilibrium, and again its inertia is responsible for it overshooting.
  - The cycle repeats. The mass simply oscillates up and down.
  - Representing the functional dependence of the mass's elevation on time plots:

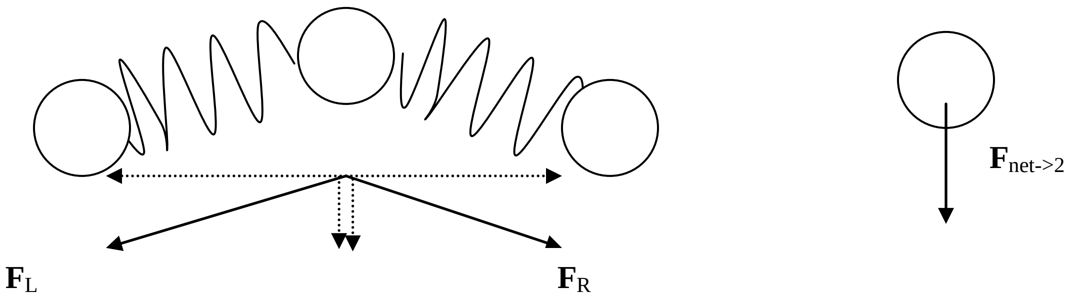


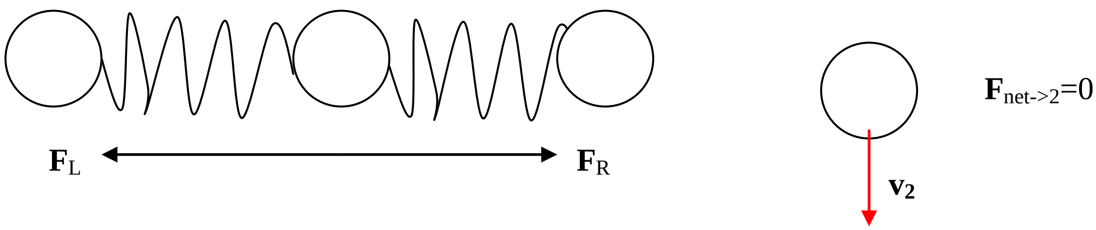
Mathematically, the functional form is $Y(t) = Y_{\max} \cos\left(2\pi \frac{t}{P}\right)$ (if we start the clock when it peaks).

- **Moral**
  - Simple Harmonic Oscillation results from two competing influences on a body's motion: a *restoring force* that pulls it toward equilibrium, and *inertia* which makes the body overshoot equilibrium.
- **Dependence of P on force and inertia**
  - The more stiffly the restoring force scales with the displacement (the stiffer the spring), the harder the object is pulled back toward equilibrium. The more massive the object, the less it responds to the force. Mathematically this interplay is seen in the expression for the period, P.
    - $P = 2\pi\sqrt{\frac{m}{k}}$, or the frequency is $f = \frac{1}{P} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$
    - **Demo: Spring** Change masses and see period change
    - **Demo: Spring** Change spring length // stiffness and see period change.
    - **Generalization –** As we'll see when we look at stringed instruments, if we're talking a plucked string instead, there's a qualitatively similar interplay – the more tense the string is, the higher the frequency, the denser the string is, the lower the frequency. In general – the frequency is determined by the balance of something to do with a restoring force and something to do with inertia
- ***Lack* of dependence on amplitude**
  - The book makes a point of noting that the frequency of oscillation *does not* depend on the amplitude.
    - **Demo: Spring** Start the mass much further down and see the same period.
    - **Louder but not higher.** When it comes to not masses on springs, but say strings of instruments, this is essential – you can play loudly or quietly and have the same basic pitch.

- I've just discussed the motion of a mass on a spring, but many other systems, such as atoms in matter, satisfy the necessary conditions, and execute motion like this when they are displaced by, say, being struck, or plucked.
- **Demo: mass-spring model of solid & rod.** Indeed, common conceptual models that physicists use for solids or strings is a bunch of masses connected by springs.
-
- **Pendulum**
  - You've probably seen the pendulum swinging back and forth in a grandfather clock or been a pendulum yourself – down at a park on a swing. It's another example of simple harmonic motion (provided the displacement is small enough) and another place where the inertia / restoring force balance determines the period
    - **Demo: pendulum**
    - Note: natural frequency of swing
      - Plot out angle vs. time
    - Start from different initial displacements. & see same period.
      - (Pendulum period)
        - $P = 2\pi\sqrt{\frac{mL}{w}} = 2\pi\sqrt{\frac{mL}{mg}} = \pi\sqrt{\frac{L}{g}}$
        - **inertia like/ force like**
- **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 kind of like the pendulum, and the frequency with which they do so depends on their stiffness & mass (distribution).
  - **Demo: tuning forks**
    - **Two different tuning forks**
      - That they differ in lengths changes both their mass and their stiffness – thus changing the frequency of resonance.
    - **Tuning fork with attached mass**
      - Note that it dramatically affects the frequency.
  - **Homework Note**: In your homework, you're asked what would happen if you attached lumps of clay to the ends of the tuning fork – that's essentially what I've done here (but lumps of aluminum instead.)
- **SHO -> Waves**
  - Now, all of these have been examples of one thing sitting wiggling in place, as opposed to a *wave* rippling along. I can at least suggest how our thinking of a single mass on a spring can be scaled up to think of a whole series of things oscillating – a wave.

- **Demo:** Torsion wave beams. First let one bob – subject to the restoring force of the twisted center bar linking it to its neighbor. Then let two, then… all twist.
- **Illustration:** Draw picture of springs between masses pulling on each other.





Then the flip to make it want to move up again.

2.5 Work, Energy, and Resonance

- **Intro: The project in physics**
  - In physics, we talk about the *motion* and *interaction* of objects.
  - **Sound Physics.** For example, in this class, we're interested in the *motion* of sound sources, how they *interact* with the air to set it *moving* and how it, in turn, *interacts* with your ear to set parts if *it* moving.
  - **Quantify with math.** In discussing these things, we try to be as precise and logical as possible, and the language of mathematics is great for that.
    - 1) mathematics is precise: in English you may say that there are a whole lot of molecules of nitrogen in this room – that's not terribly precise. In mathematics you may say that there are 3.96×10^{25} molecules. That's a bit more precise.
    - 2) the grammar of mathematics (equations) is just as precise as the vocabulary (numbers).
  - So we can use math to very precisely describe how the universe works.
  - So, we want to speak about *motion* and *interactions* in the language of mathematics. Thus we must find ways to phrase these properties in terms of hard fast numbers and logical relations in terms of equations. One way we mathematically describe motion and interactions is with
    - **Kinetic Energy** (how fast, who cares where, and how massive) & **Work** (how hard is it pushed or pulled & over what distance)

- **Work & Energy Relation**
    - **Kinetic and Potential Energy.** In physics, "energy" actually comes in two flavors – "kinetic" energy measures *actual motion* and "potential" energy measures the *potential to have motion.*
        - **Car (moving with gas) example.** For example, a moving car may have a good deal of kinetic energy associated with its speeding down the highway as well as a good deal of potential energy associated with the fuel in its tank (really, we'd need to include the air in the system to cleanly call that the system's potential energy).
            - **Mass on spring example.** A little less familiar but more on target for us today is a mass bobbing on a spring. Obviously, the faster the mass is moving, the more *kinetic* energy we'd say it has, but the more the spring is stretched/compressed from equilibrium, the more *potential* energy it has. For example, if your younger sibling has one of those spring-loaded plastic-pellet guns, you avoid getting aimed at because the cocked spring has the *potential* to make that little ball really move. Since an oscillating mass on a spring is, well, *oscillating* between moving quickly and compressing/stretch greatly, the energy is then oscillating between these two types.
                - You won't have to use these, but just so you know, for reasons we don't need to get into here, the mathematical definition of kinetic energy is $\mathbf{KE = ½\ mv^2}$, and the potential energy associated with stretching / compressing a spring is. $\mathbf{PE = ½\ k\ s^2}$
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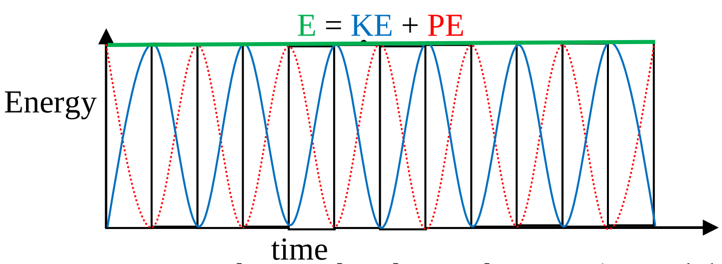
            - **Demo: Vpython mass-on-spring with energy**



Observe that the *total* energy (potential for plus actual motion) doesn't change.

- **Work = ΔEnergy.** Of course, there are ways to change something's energy – we call changing something's energy 'doing work' on it. Work is the means by which we change a system's motion (actual or potential) / its energy.
    - **Example:** kicking a ball. If a ball's just sitting here (no kinetic energy), then I kick, the kicking does positive work to get it moving, and if you catch it, you do negative work to stop it again.

- **Work = Effort * Results ($\mathbf{W = F_x * \Delta x}$)**
    - I put it to you that this is right in line with how folks think about "work" outside of physics too; we're just more specific with what we mean by "effort" and "result"

Resonance

- **Oscillating force for oscillating motion.** Let's once again come back to thinking about the mass bobbing on a spring. Since the direction of its motion periodically changes (going up, going down, going up,…), if I want to do work to *increase* its motion, then I have to time / direct my pushes and pulls properly – I want to pull down when the mass is moving down and push up when the mass is moving up.
  - **Example: driving a swing.** You probably actually have experience with something like this – who here's ever pushed someone on a swing?
    - To make it go higher and higher (or just maintain its amplitude in spite of friction in the hinge) you push in synch with the motion.
- **Resonance:** this is an example of "resonance", an oscillating system's motion increasing dramatically because it's being driven in synch with its natural motion.
  - **Demo:** Drive mass on spring at different frequencies (mass hanging from spring, with another spring hanging from it and connected to driver which sits below) (note: using lab springs and 20g mass, the resonance is around 2.7 Hz, one set up I've used was about 2.475 Hz)
  - 1 Something special happens when I drive at the frequency it likes, its natural frequency. When it's going down, I push it down – speeding it up, giving it more motion, more energy – I do positive work
  - 2 Even when I hit it randomly, it selectively moves mostly at its natural frequency – it selects out that frequency.
- **Resonance in instruments**
  - Why yammer on and on about energy and resonance in a Sound Physics course? Because Resonance plays an *essential* role in producing and perceiving sounds.
    - It takes repeated small drives and amplifies to produce big motion
    - Resonance plays a major role in taking 'noisy' drives and giving back simple harmonic motion

Next Time:

Next week we'll see this as we consider how instruments make music – Chapter 3. Have a good weekend.

- **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:
    - $v = \sqrt{\dfrac{F}{M / L}}$
  - 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
    - **Demo: Tuning Fork**

- How many pitches do you hear?
    - 2
- Of course it’s just one tuning fork, wiggling in a moderately complicated way, but our ears resolve that motion (or the resulting sound) into that 2 simultaneous simple harmonic motions.