Physics 9 — Friday, September 7, 2018

- Handing out HW #1, due next Friday in class
- For today, you read Mazur ch16 ("waves in one dimension")
- For Monday, you will read PTFP ch7 ("waves, including UFOs, earthquakes, and music")
- Course web page is `positron.hep.upenn.edu/physics9`
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A few things to remember about vibrations (periodic motion)

- Meaning of amplitude, period, frequency
- Drawing or interpreting a graph of periodic motion
- Don't confuse angular frequency vs. frequency ($\omega = 2\pi f$)
- Any system that is in stable equilibrium can undergo vibrations w.r.t. that stable position.
- Mass on spring: (natural) frequency is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

- Pendulum: (natural) frequency is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{\ell}}$$

- For a given mass, a larger restoring force (more stiffness) increases f_0.
- If the restoring force is elastic (not gravitational), then a bigger mass decreases f_0. For pendulum, f_0 doesn't depend on mass, because restoring force is gravitational.

Natural period of oscillation is **independent** of the amplitude

Mass on spring (use "0" to mean "natural"):

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad\qquad T_0 = 2\pi\sqrt{\frac{m}{k}}$$

Simple pendulum (small heavy object at end of "massless" cable):

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{\ell}} \qquad\qquad T_0 = 2\pi\sqrt{\frac{\ell}{g}}$$

For a pendulum, the period is also independent of the mass, because the restoring force (due to gravity) is proportional to mass, so the mass cancels out.

Our two favorite oscillating systems are the "mass on a spring" and the pendulum. Let's start with the mass on the spring.

- I have here a spring (of unknown "spring constant") and a known mass. How can we measure the spring constant k ?
- Force exerted by spring has magnitude $F = k\,(L - L_{\mathrm{relaxed}})$. The spring tries to go back to its relaxed length.
- What happens if I lift the bob from its equilibrium position, then let it go? How do we describe the subsequent motion mathematically, e.g. $y(t)$ for the bob?

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$$y(t) = y_{\mathrm{equilibrium}} + A\cos(2\pi f_0 t)$$

- Does the period of the motion depend on the stiffness of the spring? On the mass of the bob?

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- "frequency" $f_0 = \frac{1}{2\pi}\sqrt{k/m}$. "period" $T_0 = 2\pi\sqrt{m/k}$
- If I lift the bob up farther before letting go, will the period of the motion be the same or different?

Wednesday's skyscraper earthquake video came from
`https://mathspig.wordpress.com/2011/03/21/cool-formula-for-calculating-skyscraper-sway/`

- Under the "earthquake engineering" heading, "base isolation" (putting the building on pads or rollers) is a nice illustration of Newton's first law.
- Their second method is using a shock absorber to dissipate the vibrational energy: we saw this when we discussed resonance last year in Physics 8.
- Their third method is to use "active tuned mass dampers:" use a compuer-controller counter-moving weight to actively move against the building sway. This is analogous to using destructive interference to make one sine wave cancel out another sine wave.

Here, just FYI, I stumbled upon an academic site studying the performance of tall buildings:

`http://www3.nd.edu/~dynamo/tall_bldg.html`

Waves

If you have a very long chain of things that

- behave like oscillators when their neighbors are held fixed
- cause their neighbors to respond proportionally to their own motion

then **waves** can propagate along that chain.

In a taut wire (e.g. piano string), speed of wave propagation is

$$v = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{\text{tension}}{\text{mass/length}}}$$

Wave speed is a property of the medium.

More tension $\rightarrow$ faster propagation.
More mass per unit length $\rightarrow$ slower propagation.

Waves

Waves can be *transverse* or *longitudinal*, depending on whether the motion of the individual oscillators is $\perp$ or $\parallel$ to direction of wave propagation. You can make a slinky transmit either kind of wave.

You can make a single *pulse* propagate as a wave, or you can have *periodic* waves that repeat again and again.

Periodic waves at a single frequency f ("harmonic waves") are sinusoidal and have *wavelength*

$$\lambda = \frac{v}{f}$$

Usually people remember this as $v = \lambda f$.

Question (to wake everyone up!)

Suppose that I am wiggling one end of a taut string to create sinusoidal waves. If I double the frequency f at which I wiggle the end, how does the wavelength λ change?

(A) The new wavelength is double the original wavelength

(B) The wavelength does not change

(C) The new wavelength is half the original wavelength

Sound waves in room-temperature air travel at a wave speed of 343 m/s. (Much more on sound next week!)

Digression: About how long does it take for a pulse of sound (maybe a clap of thunder or the sound of a baseball bat hitting a ball) to travel 1 km?

What about a mile (1.61 km $\approx$ (5/3) km)?

What about one foot ((1/3.28) meter, or (1/5280) mile)?

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Sound waves in air travel 1 km in 3 s, 1 mile in 5 s,
1 foot in 1 millisecond.

Sound waves in room-temperature air travel at a wave speed of 343 m/s. At a frequency of about 34 Hz (near the lower end of the range of frequencies people can hear), what is the wavelength?

(Young human ears can hear roughly 20 Hz — 20 kHz.)

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It turns out that the conventional telephone network only transmits sounds in the frequency range 300 Hz — 3400 Hz. What's the wavelength (for sound in air) at 343 Hz? At 3430 Hz?

Waves

The ideal situation for a wave pulse is to propagate forever down an infinitely long string (or wave machine). When you shout into a completely open field, there is no echo!

But sometimes the wave runs into an obstacle. The three easiest cases to analyze are

- The far end of the string is clamped, immobilized:
  reflected pulse has opposite sign as incident pulse
- The far end of the string is unconstrained ("free"):
  reflected pulse has same sign as incident pulse
- The far end has a "terminator" or "dashpot" or "damper" that perfectly absorbs all of the incoming wave's energy:
  no reflected pulse

Interference / superposition

A weird property of waves is that two waves can pass right through one another. Whereas particles bounce off of one another, a wave is not an obstacle to another wave. The two waves' displacements add up (algebraically), including their signs.

- A peak and a peak add to a larger peak
- A peak and a trough can add to zero
- Whether they add constructively or destructively depends on the relative phases of the two waves

In one dimension, the big consequence of interference is that one wave traveling to the right and an equal-size wave traveling to the left will add up to form a *standing wave*.

In 2 and 3 dimensions, it gets much more interesting: if you have two separated speakers playing the same tone, there will be some places in the room where the amplitude is twice as large, and some places in the room where the amplitude is zero! Noise-canceling headphones use destructive interference of waves.

Wave movies

(I just re-wrote my wave "movies" as Processing sketches. I used the Python version of Processing rather than the original Java version of Processing that some of you learned last year, as I hear that Python is more useful to you than Java.)

- `wave1py` : two pulses passing through each other
- `wave2py` : wave pulse reflected by boundaries
- `wave3py` : two traveling waves add, forming standing wave if magnitudes are same
- `wave6py` : standing waves

Question

Looking at the reflections in the animation `wave2py`, do the left and right ends of the string appear to be fixed or free? (Sketch should be playing on screen.)

(A) Left and right ends are both held fixed

(B) Left and right ends are both free

(C) Left end is free and right end is fixed

(D) Left end is fixed and right end is free

Standing waves

If you clamp both ends of a string of length L, then for harmonic waves λ is forced to obey (where $n = 1, 2, 3, \ldots$)

$$n \cdot \frac{\lambda}{2} = L \quad \Rightarrow \quad \lambda = \frac{2L}{n} \quad \Rightarrow \quad f = n \cdot \frac{v}{2L}$$

An integer number of **half-wavelengths** must fit in length L.

Combining this with $\quad v = \sqrt{\frac{T}{m/L}} \quad$ we get

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{m/L}}$$

More massive wire $\rightarrow$ lower f. Higher tension $\rightarrow$ higher f.
Make string shorter with fingertip $\rightarrow$ higher f.

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