HW1 due Monday 1/25. If Newton’s laws are fresh in your mind from Physics 8, you can get through it in an hour or so.

Homework help: (Bill) Thursdays, 6-8:30pm, DRL 2N36; (James=TA) Sundays, 5-7pm, DRL 2N36.

For today, you read Mazur’s ch16 (1D waves). I like the detailed illustrations of what makes a wave propagate. When we read chapters from Mazur’s book, don’t let yourself get bogged down in the math: follow the ideas.

For Wednesday, you’ll read Giancoli ch12 (sound).

For next Friday, you’ll read a couple of short articles about architectural acoustics, then you’ll read/skim the introductory chapter of an Architectural Acoustics textbook, which I hope you’ll find interesting. Let me know if you’d like to read, for extra credit, more chapters on Architectural Acoustics.

Today: a couple of things to help you with HW1, and we’ll get started with waves.
My favorite problem from HW1 is #7.

7*. Three blocks on a frictionless horizontal surface are in contact with each other, as shown below. A force $\vec{F} = 90.0 \text{ N}$ (pointing to the right) is applied to block A (mass $m_A$). The blocks’ masses are $m_A = m_B = m_C = 10.0 \text{ kg}$. 
(a) Draw three free-body diagrams: one for each block. (In this problem, just focus on the horizontal forces, since the two vertical forces on each block will sum to zero.) 
(b) Find the acceleration of the three-block system. 
(c) Find the net force (magnitude and direction) acting on each block. 
(d) What are the magnitudes and directions of the two horizontal forces acting on block A? 
(e) What are the magnitudes and directions of the two horizontal forces acting on block B? 
(f) What are the magnitude and direction of the one horizontal force acting on block C?

The blocks are rigid (inflexible) and are touching. When I push the left block toward the right, will the blocks all have the same acceleration? If so, how do I find that acceleration?
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If you know the acceleration of each block, and you know the mass of each block, how do you find the net force acting on each block?
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 $F = k (L - L_{\text{relaxed}})$. 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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$$y(t) = y_{\text{equilibrium}} + A \cos(2\pi f_0 t)$$

- Does the period of the motion depend on the stiffness of the spring? On the mass of the bob?
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► Force exerted by spring has magnitude \( F = k (L - L_{\text{relaxed}}) \). 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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\]

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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?
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

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

- 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.
- Pendulum: (natural) frequency is . . .
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\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{\ell}}
\]
Natural period of oscillation is **independent** of the amplitude
(“Natural” means we just displace it once and let it oscillate at its
own built-in frequency. We’re not pushing it periodically.)

Mass on spring (use “0” to mean “natural”):

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad T_0 = 2\pi \sqrt{\frac{m}{k}}
\]

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

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{\ell}} \quad T_0 = 2\pi \sqrt{\frac{\ell}{g}}
\]

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.
Wednesday’s 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 in December.
- Their third method is to use “active tuned mass dampers:” use a computer-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 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 $\lambda$ 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.

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) \text{ km})?

What about one foot ((1/3.28) \text{ meter, or } (1/5280) \text{ mile})?

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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At a frequency of 34300 Hz (about 2× above the upper limit of human hearing), what is the wavelength?
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What is the wavelength at 17150 Hz, which is close to the (roughly) 20 kHz upper range for young human ears?
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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

http://positron.hep.upenn.edu/p9/files/wave1.mp4
  ➤ wave1.mp4: two pulses passing through each other
  ➤ wave2.mp4: wave pulse reflected by boundaries
  ➤ wave3.mp4: two traveling waves add, forming standing wave if magnitudes are same
  ➤ wave6.mp4: standing waves

Opportunity for extra credit: redo these animations as Processing sketches!
Question

Looking at the reflections in the movie wave2.mp4, do the left and right ends of the string appear to be fixed or free? (Movie 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 \( \lambda \) 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 \( v = \sqrt{\frac{T}{m/L}} \) we get

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

More massive wire → lower \( f \). Higher tension → higher \( f \). Make string shorter with fingertip → higher \( f \).
Random note: Note that this table is energy **per gram**. So e.g. it’s not that a flashlight battery stores more energy than a car battery, but that it stores more energy **per gram**. Also, implicit in each row is some mechanism of energy release. Not counting the $O_2$ needed for combustion is “cheating” for a spaceship, but it’s **not** cheating for a terrestrial animal or vehicle, since air is 21% $O_2$.

<table>
<thead>
<tr>
<th>Object</th>
<th>Calories (or watt-hours)</th>
<th>Joules</th>
<th>Compared to TNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet (at sound speed, 1000 ft/s)</td>
<td>0.01</td>
<td>40</td>
<td>0.015</td>
</tr>
<tr>
<td>Battery (auto)</td>
<td>0.03</td>
<td>125</td>
<td>0.05</td>
</tr>
<tr>
<td>Battery (rechargeable computer)</td>
<td>0.1</td>
<td>400</td>
<td>0.15</td>
</tr>
<tr>
<td>Flywheel (at 1 km/s)</td>
<td>0.125</td>
<td>500</td>
<td>0.2</td>
</tr>
<tr>
<td>Battery (alkaline flashlight)</td>
<td>0.15</td>
<td>600</td>
<td>0.23</td>
</tr>
<tr>
<td>TNT (the explosive trinitrotoluene)</td>
<td>0.65</td>
<td>2700</td>
<td>1</td>
</tr>
<tr>
<td>Modern high explosive (PETN)</td>
<td>1</td>
<td>4200</td>
<td>1.6</td>
</tr>
<tr>
<td>Chocolate chip cookies</td>
<td>5</td>
<td>21,000</td>
<td>8</td>
</tr>
<tr>
<td>Coal</td>
<td>6</td>
<td>27,000</td>
<td>10</td>
</tr>
<tr>
<td>Butter</td>
<td>7</td>
<td>29,000</td>
<td>11</td>
</tr>
<tr>
<td>Alcohol (ethanol)</td>
<td>6</td>
<td>27,000</td>
<td>10</td>
</tr>
<tr>
<td>Gasoline</td>
<td>10</td>
<td>42,000</td>
<td>15</td>
</tr>
<tr>
<td>Natural gas (methane, $CH_4$)</td>
<td>13</td>
<td>54,000</td>
<td>20</td>
</tr>
<tr>
<td>Hydrogen gas or liquid ($H_2$)</td>
<td>26</td>
<td>110,000</td>
<td>40</td>
</tr>
<tr>
<td>Asteroid or meteor (30 km/s)</td>
<td>100</td>
<td>450,000</td>
<td>165</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>20 million</td>
<td>82 billion</td>
<td>30 million</td>
</tr>
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Note: Many numbers in this table have been rounded off.
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