Science-1A Lab: Week 3, Wednesday, January 27, 2021

This lab will be a combination of imagining what we might do together in groups, and what you can actually do at home.

Dropping Marbles and Books

In the lab, tape markers are put on various parts of the surrounding wall at 2.00 m, 1.50 m and 1.00 m above the floor with a clear drop path to the floor. To protect the marbles and floor, 20 cm x 20 cm cardboard squares are laid on the floor to act as a cushion. At the different heights, one student will drop a marble, another will time the fall with a timer on their phone that has a 0.01 s resolution, and a third student will write the result and recover the marble. This is done with small 1.5 cm diameter marbles, and also with larger 2.5 cm diameter ones.

This is at best a very crude measurement because of the uncertainty in the timing. Even when saying "3, 2, 1, 0" to help synchronize everyone with the release time, and with the sound of the marble hitting, the timing error is considerable. Repeating the drops at each height 10 times helps reduce random errors, but any systematic reaction-time problem is not reduced by averaging repeated measurements.

The students then use a web application linked at the top of *http://yosemitefoothills.com/Calculator/* entitled "Calculate mean and standard deviation of a set of numbers" to get the average and standard deviations of each group of "identical" drops. (Most scientific calculators can also do that calculation.)

One group of students improved their measurements considerably by video taping the drop and playing back the video in slow motion.

The formula describing a dropping object from a height *h* when air resistance can be ignored is $h=\frac{1}{2}gt^2$ which we rearrange to become $t=\sqrt{\frac{2h}{g}}$ with *g* being the acceleration of gravity at the surface of the Earth. We usually use g=9.80 m/s^2, so the theory gives t = 0.639 s, 0.553 s, and 0.452 s, for our heights of 2.00 m, 1.50 m, and 1.00 m, respectively. The times for the heavy marble and light marble should be indistinguishable as Galileo Galilei is said to have demonstrated long ago with a higher drop.

Just for fun, I dropped a rock from a platform in our pond garden with a camera taking a video of the falling rock. Analysis of that video is at
http://yosemitefoothills.com/Science-1A/Handouts/Week-01/FallingRockAnalysisWithData.pdf .
This analysis has more detail than you are expected to absorb, but I hope you take a look at it to see what you might use to challenge your extra ambitious students.

In class, I often drop a book to prove a point about gravity. I would like you to do the following with your textbook or a similarly-sized book. The textbook is larger than a normal sheet of paper (if not, trim the paper a bit) which you will also drop. First drop them in a flat orientation side-by side separated by about 50 cm. The book will quickly go thud, but the paper will flutter down later. That, of course, is because of air resistance. The paper is acting more like a parachute. The heavier book, just pushes the air out of the way without experiencing any significant resistance.

Now for the fun part. Place the paper on top of the flatly-orientated book, and then let them fall together. With the book pushing the air out of the way, the sheet of paper cannot be pushed by the air and falls together with the book. That shows that if air resistance were not a factor, the book and paper would fall at the same rate.

Using Work, Energy, and Power to think about Falling (and Rising) Objects

In this section, I assume you have watched the Crash Course videos mentioned in Monday's note.

If we start with the book on the floor, we can declare the floor as the point of zero gravitational potential energy. We say it has no kinetic energy because it is not moving (we ignore the fact the Earth is whirling through space). If it has a mass of 2 kg, its weight will be $\text{weight}=mg=(2\,\text{kg})\cdot(9.80\,\text{m/s}^2)=19.6\,\text{N}$ directed downward, and the floor will be pushing it up with a balancing force of 19.6 N directed upward. Those forces cancel so there is no net force on the book, and it does not accelerate − it just rests there.

Then, we take the book and lift it with a force of slightly greater than 19.6 N. It will start moving upward at which point, we adjust our lifting force exactly to 19.6 N. I will then continue its slow upward motion until, at 2 m above the floor, we reduce our lifting force slightly until the book stops moving. We are now holding the book 2 m above the floor using our muscular force of 19.6 N to balance its weight. It is not moving, but now has a gravitation potential energy of

$$E = m\,g\,h = (2\ \mathrm{kg})\cdot(9.80\ \mathrm{m/s^2})\cdot(2\ \mathrm{m}) = 39.2\,\frac{\mathrm{kg\cdot m^2}}{\mathrm{s^2}} = 39.2\ \mathrm{J}$$

That energy came from our muscles doing work. Our lifting force (the book's weight) multiplied by the distance it moved in response to that force is the work, $\text{work} = F\cdot d = m g\cdot h$. Its gravitational potential energy came from the work we did lifting the book against gravity. That energy, in turn, came from food we ate, which came from plants (maybe via animals), which came from sunlight, which came from nuclear fusion reactions of hydrogen nuclei in the sun.

Now, here is the part you will not like. If we hold the book still at 2 m above the floor for a day, we are doing no additional work even though our muscles are getting tired. We are burning food calories, but not doing mechanical work. This is discussed at length in the handout at *http://yosemitefoothills.com/Science-1A/Handouts/Week-03/ReconcilingBiologicalAndPhysicsEnergyConcepts.pdf* .

Think of it this way. We could have just put the book on a shelf 2 m high and walked away. We would be doing no work and the book would still have its 39.2 J of gravitational potential energy.

You may not like this next part either. If you lower the book slowly to the floor, gravity will then be doing work on you! That is not easily noticed, but after all, it **is** easier to go downstairs than upstairs. Our bodies cannot use that energy very well, but a kangaroo can as it bounces along using its muscles like springs.

Remember that kinetic energy comes from a mass having some speed $KE = \frac{1}{2} m v^2$. If you drop the book, it will gain speed according to $v = g\,t$ and therefore gain kinetic energy $KE = \frac{1}{2} m (g\,t)^2$. We know from the beginning of this note that the time for something to fall from a height *h* is $t = \sqrt{\frac{2h}{g}}$. Using this time in our formula for kinetic energy gives $KE = \frac{1}{2} m \left(g \sqrt{\frac{2h}{g}} \right)^2 = m\,g\,h$. By the time the book has fallen back to the floor, it has gained in kinetic energy by exactly the amount of potential energy it had when resting up at 2 m:

$$PE_{2\ \mathrm{m}} = KE_{0\ \mathrm{m}} \quad \text{or} \quad m\,g\,h = \frac{1}{2} m v^2 \ .$$

If you cancel the *m*'s on both sides of this equation, multiply both sides by 2, and take the square root, you end up with $v = \sqrt{2 g h}$, a formula that tells you how fast the book is moving when it hits the floor. At that time, its kinetic energy gets abruptly converted to sound and heat energy.

Have you used a Pogo Stick? (Look it up on YouTube.) Trampolines and Pogo sticks are able to store energy efficiently and then give it back with little loss.

A coasting car, bicycle, or roller-coaster gains kinetic energy going downhill and gets to use it on the next uphill.

Hybrid and electric vehicles store their extra kinetic and gravitational energy in a large battery so it can be used later when needed. If a car could be made with no air resistance, frictionless wheels, perfectly-efficient motors/generators, and a very large-capacity perfect battery, it could start at Kaiser Pass, descend to Clovis, and then return to Kaiser Pass without using any gasoline. The limit on hybrid vehicle efficiency is the cleverness of engineering and properties of materials, so expect vehicle efficiency to continue to increase in the coming decades. My first car had about 18 mpg. Before a rabbit totaled my 2003 Prius in 2018, it averaged about 50 mpg. My 2016 replacement Prius averages 60 mpg (as long as traffic allows me to drive gently). The rabbit, by the way, got under the hood and ate through wiring and an inaccessible fuel line.

Above Fresno are Courtright and Wishon Reservoirs which form an interesting system of energy storage. Courtright is at an elevation of 2490 m and Wishon is at 1998 m. When the PG&E power company needs more electricity, water is sent down large pipes to generators at Wishon, draining down Courtright Reservoir. At night, when there is extra power available in the grid, pumps at Wishon send the water back up to Courtright. The gravitational potential energy of the water is being used to store electrical energy.

Pendulums

Once children hop on a swing they become part of a pendulum. Before long, they learn the rather sophisticated process of "pumping" the swing by leaning back and sitting up at the right points of the swing's movement. They can then add energy and get it to go higher. The mathematics for pumping a swing are quite complicated, but the basics of pendulum motion for small angles are instructive.

The simplest pendulum equation is $T=2\pi\sqrt{\frac{l}{g}}$ where T is the period of the pendulum's complete swing (to and fro), l is the length from a rigid suspension point down to the center of mass of the swinging mass m. Notice that the formula does NOT depend on the mass. That is for same reason that, ignoring air resistance, all masses fall at the same rate.

Now, consider 3 pendulums that have lengths of 1.00 m, 1.50 m and 2.00 m. Their periods will be

$$T_{1\,\mathrm{m}}=2\pi\sqrt{\frac{1\,\mathrm{m}}{9.80\,\mathrm{m/s^2}}}=2.007\ s \qquad T_{1.5\,\mathrm{m}}=2\pi\sqrt{\frac{1.5\,\mathrm{m}}{9.80\,\mathrm{m/s^2}}}=2.458\ s \qquad T_{2\,\mathrm{m}}=2\pi\sqrt{\frac{2\,\mathrm{m}}{9.80\,\mathrm{m/s^2}}}=2.838\ s$$

A pendulum-based clock will often have a pendulum that is very close to 1 m long so that it swings back and forth with 1 second for each direction of swing.

The simple formula is based on 3 key assumptions:

1. That the swinging mass is much greater than the mass of the wire, string, or bar connecting it to the pivot point.
2. That the angle of swing is rather small, like ± 5 degrees or less.
3. That the mass is sufficiently dense that air resistance will have a negligible effect at slowing it down.

In lab, we use lead fishing weights, ideally ball-shaped, with a hoop to attach the string or wire. We also have clips that attach to the cross-bars supporting the ceiling tiles. The string or wire needs to be light, but not so light that it will be stretched by the weight of the mass. Music wire is ideal, but kite string will do. If you do not have a fishing weight, look around for some compact object that you can use that weighs between 20 and 100 grams.

Timing is best done with the 0.01 s precision possible from many phones or racing stop watches. The time is measured for 20 complete swings (to and fro). The value for *T* will then be the measured time divided by 20. This should be done for two lengths of about 1 m and 2 m. Those lengths do not need to be exactly 1 m and 2 m, but must be measured carefully from the pivot point to the center of the mass. Try for an accuracy of ± 2 mm.

These measurements do not take very long after you have made the pendulum.

Here are the forms for your data. The "20 T" column is the total measured time in seconds for 20 complete swings, and the "Period T" column values are the "20 T" column values divided by 20. Be sure to write down the length *l* and the theoretical period you calculate from that length T_{Theory}. There are 5 groups of measurements for each length. Independent repetitions of measurements help reveal measurement errors.

Mass of weight (should have no effect on period, but nice to know): ______________ g

Data for short pendulum (about 1 m length)

Actual length *l*: ________________ m $\qquad T_{\text{Theory}} = 2\pi\sqrt{\frac{l}{g}}$ = ______________ s

Run #	**20 *T* (seconds)**	**Period *T* (seconds)**
1		
2		
3		
4		
5		

Data for long pendulum (about 2 m length)

Actual length *l*: ________________ m $\qquad T_{\text{Theory}} = 2\pi\sqrt{\frac{l}{g}}$ = ______________ s

Run #	**20 *T* (seconds)**	**Period *T* (seconds)**
1		
2		
3		
4		
5		

The following 3 short videos must also be watched for the lab credit.

Dartmouth Professor Discusses Foucault's Pendulum
https://www.youtube.com/watch?v=aMxLVDuf4VY . (3 min 20 s)

Coupled Pendulum
https://www.youtube.com/watch?v=CjJVBvDNxcE . (3 min 28 s)

Trust in Physics
https://www.youtube.com/watch?v=xXXF2C-vrQE . (2 min 8 s)

To get the lab points do the following:

1. **Carefully follow the instructions for doing the pendulum measurements** and tell me what you used for a string and weight, and how you suspended it.
2. Calculate the theoretical period of your pendulum, fill in the tables, and send me a picture of them attached to your submission. Don't forget to write the actual length of each pendulum.
3. Tell me that you watched the three videos linked above.

Consider February 7 as the due date for this effort.