Coupled Pendulums

Grade(s): MS
Topic: Physical Science

Standards:

Disciplinary Core Ideas
MS-PS3-2 Develop a model to describe that when the arrangement of objects interacting at a distance changes, different amounts of potential energy are stored in the system.
MS-PS3-5 Construct, use and present arguments to support the claim that when kinetic energy of an object changes, energy is transferred to or from the object.

Science and Engineering Practices:
Engaging in argument from evidence
Asking questions and defining problems
Planning and carrying out investigation
Constructing explanations and designing solutions.

Objective:
Understand that energy can be transferred from object to object.
To determine what variables affect the period of a complex pendulum.
To create a solution to knock a domino over between 3 to 4 seconds after a human interaction (after starting the system).

Materials:
String
Nuts (or other weights)
Tape
Scissors
Dominos (or other tippable object)
Optional stand: 96" length 1/2" PVC, 2 elbows, 2 T's, 2 end caps.

Advanced Preparation:
Pre-cut PVC for stands if you are using stands, or pre-built stands.

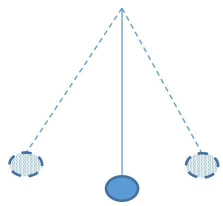
Activity

Part 1

Show students a single pendulum. Ask where the energy comes to lift up the pendulum, where will it go when you let go of the pendulum. Ask where along the pendulums path it would hurt the most if it were to contact you? Would it hurt more if it's going fast or slow? Discuss.

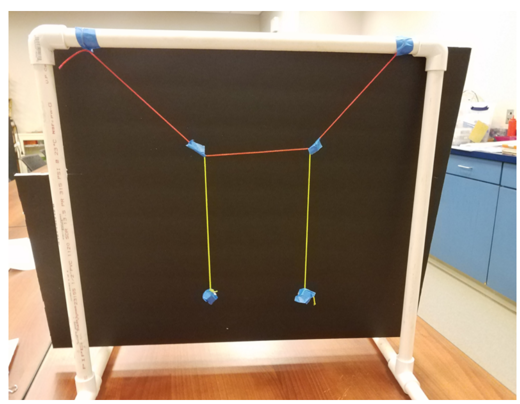
Take a moment to experiment with this very quickly. Tell everyone to make a simple pendulum by tying a knot around a nut. Holding the string and gently lifting the nut to the side and letting it go. Tell all of the students NOT to move the nut more than a little bit to the side (30 degrees) – you want to keep the students from swinging the nut wildly. Ask the students for observations. Discuss as a class.

Science backdrop: At the bottom of the pendulum's swing (pictured) the gravitational potential energy has become kinetic energy – so it's going the fastest. Because it's going fastest at the bottom, that's also probably the point at which it could hurt you the most.



Part 2

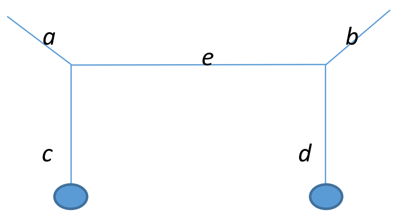
Show the coupled pendulum setup (pictured). This consists of one string strung between two points, with two pendulums attached to the string. Ask the students what they think will happen if you lift one pendulum towards you and let it swing. Tell them to make predictions. As a class, observe and discuss.



Ask the students what pushed on the string to make the second pendulum move. When you hold a single pendulum, by the string and swing it, you can feel the pendulum gently tug your fingers when it goes from side to side. This "tugging" is what transfers energy to the second pendulum.

Ask the class what variables could they alter that **might** change the time it takes for energy to transfer from one pendulum to another. List these on the board. If students say "change the length, tell them to be more specific. There are multiple lengths in each pendulum. There is the length from the rigid pole to the first pendulum, the distance between pendulums, the length of each bottom pendulum. Is the height change important? Or the length of the string? The students could experiment with any of the lengths. They could also experiment with the same or different weights. Let the students know that right now, the length a = b and c =d and the weights are the same. Tell the students they have two goals (or you can divide this into two separate lessons – each with one goal):

1) Determine what affects the amount of time it takes for the energy to transfer from one pendulum to another pendulum. What variable(s) do you need to modify to change the time frame? Be specific – record what you altered, and how it changed the time. Have at least three points of data prior to drawing any conclusion.
2) Design a pendulum apparatus that knocks over a domino in between 3- 4 seconds after they release the pendulum. They will not be given the domino in advance, but they will be given its dimensions. They will be able to position the domino prior to beginning, but they can not touch the domino once the timing begins. Constraints: The apparatus can't be wider than 2'. They cannot touch the pendulum apparatus once the timing begins. If they fail, they can try to modify their apparatus in order to achieve success during a second trial.



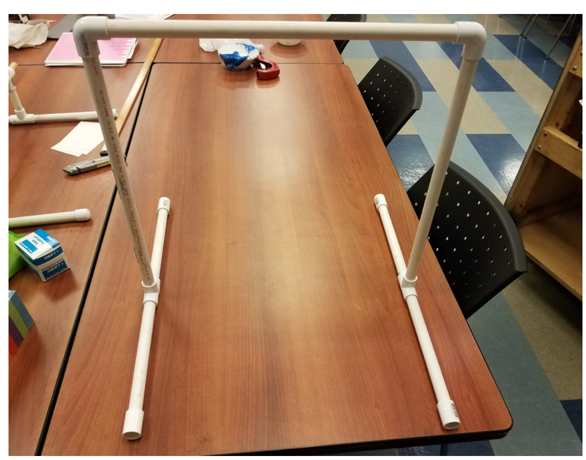
Hints: Use the tape to easily change the length(s) of the string, and to ensure that the two pendulums don't slip together and start hitting each other. Use the dimensions of the domino to create a model and figure out where to put the domino.

Modifying this activity: You can set up additional constraints on the apparatus such as fixing the length of c to 5", or stating that the domino has to be standing directly on the floor or desk. You can make this activity easier by giving the students a domino to experiment with.

Discussion: Ask the students what variables they changed in order to change the length of time it takes for the energy to transfer from one pendulum to the other pendulum. There will probably be different answers, since changing the distance between the two pendulums (*e*) results in lengths (*a*) and (*b*) changing as well (unless the length of the full string is modified).

Building the optional stand

The PVC stand is one way to hang the pendulum. This eliminates the need for someone to hold a stick to hang the pendulums off, and it eliminates the need to hang the string between objects like chairs and desks – although that is a fine way to carry out this activity. The optional stand consists of two upright pieces of PVC, connected across the top using an additional piece of PVC along with two elbows. At the bottom we use two tees as well as two end caps (or connectors) so that it doesn't wobble.



Further Challenge

You’ve now experimented with coupled motions – where one pendulum pulls on another to create motion. Now try to decouple the motion. Decoupling means that when one pendulum swings it won’t affect the second pendulum. How can you minimize or even eliminate the transfer of energy from one pendulum to the other?

Underlying Science:
The energy transfer is a *beat frequency* – caused by the interaction between the two swings. Every time pendulum A swings, it pushes on the string, which in turn pushes on Pendulum B –transmitting energy to pendulum B. According to Newton’s 3rd law (equal and opposite force), pendulum B pushes back on Pendulum A, slowing it down and taking energy from it! This happens very regularly –so regularly it can be calculated – since it is essentially two pendulums – one the full length, and one from where the individual pendulums contact the string. Appendix A includes an activity sheet taking people through the calculation for two identical length pendulums attached to the same string. The period and the frequency of the pendulums are determined by the length of the pendulum (downwards, not the overall length of the string).
Although energy transfer between coupled objects can be significantly shifted by changing the lengths and weights of the pendulums, in order to truly get rid of the coupling, you need to start attaching the pendulums to different objects.

LIGO Connection:
LIGO’s mirrors are pendulums hanging inside a chamber. Because they are pendulums they are somewhat de-coupled from the higher frequency ground vibrations, but they can still vibrate when lower frequency vibrations high the chamber. LIGO works to decouple all ground motion from its instruments. LIGO’s sensitive optics are on a foundation that is separate from the foundation of the building – but it’s connected by caulking. This **helps** to decouple the optics, but it doesn’t completely eliminate it. Much of LIGO’s engineering efforts go into decoupling the sensitive instrument from the surrounding environment, so that it can detect gravitational waves.

Resources:
https://www.ligo.caltech.edu/LA/system/media_files/binaries/301/original/Coupled_pendulums_.pdf?1472486583
https://www.exploratorium.edu/snacks/coupled-resonant-pendulums

Safety Considerations:
Nuts dropped on toes or thrown could be a hazard. Cutting/stabbing hazard due to scissors.

Appendix A

Coupled Resonance
Beat Frequency

A LIGO-SEC interactive version 3.14

Gently push pendulum A (perpendicular to the horizontal string), and watch what happens.

Every time pendulum A swings, it pushes on the string, which in turn pushes on Pendulum B – transmitting energy to pendulum B. According to Newton's 3rd law (Equal and Opposite Force), pendulum B pushes back on Pendulum A, slowing it down and taking energy from it! This happens very regularly – so regularly it can be calculated.

Pull Pendulum A and Pendulum B to the same side and let them swing – they should swing without changing their swing (much) – this is a stable swing. Do steps 1-3.

1) Time 10 swings.
2) You've got the period of 10 swings, so divide by 10 to get the period of one swing (the number of seconds per swing).
3) Invert this to get the frequency (the number of swings per second).

	# Swings	Total Time	Period of 1 Swing	Frequency
Same Side				
Opposite Side				

Pull Pendulum A and Pendulum B to opposite sides and let them swing – they should swing without changing their swing (much) – this is a stable swing. Do steps 1-3 again for this situation.

Subtract the frequency for Opposite side swinging from the frequency for same side swinging. That's the beat frequency. Invert (1/frequency = period) this to find the beat period (how long it takes to make one complete transfer of energy from pendulum A to pendulum B and back to pendulum A again. Check to see is you were accurate by swinging just one pendulum.

A) Time 10 (or if you're impatient, just 5) complete energy transfers if you can.
B) Divide the time by 10 (or 5 if you were impatient) to see if the actual beat period matches your calculated beat period!