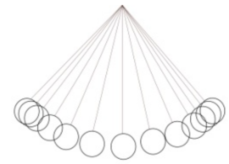
INVESTIGATING PENDULUMS

University of California, Berkeley
Adapted from FOSS "Swingers" activity



OVERVIEW:
This lesson introduces students to variables and controlled experimentation as they study how different features of a pendulum affect how it swings. Students will build and observe a simple pendulum, identify variables that might affect how fast it moves, and conduct controlled experiments to study the effect of specific variables (bob mass, release position and string length) on the number of swings the pendulum makes in 15 seconds. By manipulating one variable and keeping others constant they gain experience with the concept of a variable and in using experiments to understand the relationships between variables. The pendulum is a simple system and is good for introducing experiments as there are several easily manipulated variables and consistent outcomes. The pendulum also introduces the physical principles of gravity and inertia.

PURPOSE:
In this lesson students will:
- Use systematic thinking and reasoning to discover how pendulums work.
- Identify variables.
- Conduct an experiment
- Make graphs
- Use graphs to explore the relationships between two variables and interpret results.
- Introduce the physical principals of gravity, inertia, energy.

BACKGROUND:

About Pendulums

A **pendulum** is any object that hangs from a fixed point (also called a pivot) on a string and, when pushed from its resting position, swings freely back and forth. The downward swing of the object is caused by the pull of **gravity**. The upward swing of the object is due to **inertia** (the tendency of an object, once in motion, to stay in motion, Newton's First Law). Think of a playground swing -- the swing is supported

by chains that are attached to fixed points at the top of the swing set. When the swing is raised and released, it will move freely back and forth. The swing moves due to the force of gravity pulling the swing down and inertia bringing it back up. The swing continues moving back and forth until **friction** (between the air and the swing, and between the chains and the attachment points) slows it down and eventually stops it. If there was no friction, the swing would just keep on swinging! The "frequency" of a pendulum is the number of swings or cycles it will make, back and forth, from its release position – in a unit of time. The frequency is dependent mainly on the length of the string. As the length is decreased, the frequency increases. As the length increases, the frequency, or number of swings, decreases. The length of the pendulum is the critical variable that determines the number of swings a pendulum will make in a unit of time.

Some amusement park rides are, like swings, also based on pendulums, such as the Pirate Ship and Fireball rides at the Santa Cruz Boardwalk. But pendulums can do more than entertain. With its regular swings, the pendulum has been used in clock-making, as in cuckoo or grandfather clocks. In the mid-1800s, one of the most famous pendulums, Foucault's pendulum, was used to demonstrate that the Earth rotates. Pendulums can also be used as seismometers to detect earthquakes, to measure local gravity, and as part of the guidance systems of ships and aircraft.

About controlled experiments
Scientists investigate all kinds of questions in an effort to understand the natural world. The important thing about science is that it uses evidence gathered from the natural world to test ideas. The controlled experiment is one tool that scientists use to do this. An experiment is a test that involves isolating and manipulating some factor in a system in order to see how that factor affects an outcome. The manipulated

variable is called the independent variable. The thing that is measured, the outcome, is called the dependent variable. A controlled experiment often compares the results obtained from experimental trials against *control* or standard trials. Ideally, the control or standard is identical to the experimental sample except for the manipulated factor whose effect is being tested (the independent variable). Good experiments should control as many other factors as possible in order to isolate the cause of the experimental results. In addition, experiments are usually repeated, or replicated, to guard against spurious results, mistakes and biases.

Experiments can be quite simple tests set up in a lab — like rolling a ball down different inclines to see how the angle affects the rolling time. Or they can be large scale and complex, such as the classic experiments in ecology that involved removing a species of barnacle from intertidal rocks to see how that would affect the growth and survival of other barnacle species living there. Whether large- or small-scale, performed in the lab or in the field, or requiring years or mere milliseconds to complete, experiments are distinguished from other sorts of tests by their reliance on the intentional manipulation of some factors and the control of others. There are many simple experiments that can be done in classrooms using common materials. For example, you can study how mass or the length of a pendulum affect how fast it swings. Or you can study how different features of balls (material, size) affect the number or height of bounces. Or how the incline of a ramp affects the distance or speed that a marble will roll. Just do an experiment to compare how changes in a variable that you manipulate (independent variable) affect the outcome or performance (dependent variable), while keeping other factors constant.

VOCABULARY:

Pendulum: An object (bob) attached to a fixed point by a string or rod so that it can swing freely under the influence of gravity and acquired momentum.

Bob: the mass at the end of the string or rod of a pendulum

Period or cycle: The time for one full swing of the pendulum (back and forth). The period of a pendulum can be described mathematically as: $\mathbf{P = 2\pi\sqrt{l/g}}$ where **P** =period, π = 3.14, **l** = length of string, from fixed pivot at top to center of gravity of bob, **g** = force of gravity, 9.8 m/sec^2 (Earth's gravitational constant)

Frequency: the number of full swings or periods in a specific length of time.

Gravity: the Earth's force that pulls everything downward

Inertia: The property of an object to stay moving unless it is stopped by an outside force, aka Newton's First Law

Newton's First Law: An object in motion stays in motion and an object at rest stays at rest, unless acted upon by an outside force.

Friction: resistance to motion, a force (friction of the pendulum with the air and at the pivot point causes kinetic energy to be lost and slows down the pendulum, eventually stopping it).

Controlled experiment: In its simplest form, a controlled experiment is one in which only one variable is manipulated so that its effect can be determined by comparison with a control trial. The control is the trial in which nothing was changed, it is the standard with which you compare the results of your manipulation.

Variable: anything that can change in an experiment; there are three kinds of variables to consider -

- **-independent variable** – this is the variable that you are testing, the thing you vary to see how it affects the outcome or dependent variable (in this activity variables include string length, bob mass and drop angle)
- **-dependent variable** or response variable – this is the thing you measure (in this activity it is the number of full swings a pendulum makes in 15 seconds)
- **- control variable** – these are factors that are held constant during the experiment, that you don't want to influence the outcome

Prediction: an estimate based on information or experience

MATERIALS

For each pair of students you will need:

- 1- 50 cm piece of string
- 3- washers (the size of a nickel or penny)
- 1- measuring tape
- Tape
- Scissors
- Pencil
- Data sheets
- A string of longer or shorter length (see below)
- Graph paper

For the teacher:

- Extra string (about 20-40 feet)
- Stopwatch
- Chart paper
- Number-line
- Paperclips
- Additional masking tape

Prepare ahead:

50 cm strings -- cut enough for each pair of students to have 1 string of 50 cm (for part 1) *(note, you could save class time if you pre-tied the loops and marked 38 cm on the end of the string where the students will tie on the washer)*

1 - premade 38 cm pendulum to use as model for students (for part 1)

Cut strings of varying lengths, one of each of the following: (for part 2)

13 cm	20 cm	33 cm	90 cm
15 cm	22 cm	45 cm	120 cm
17 cm	25 cm	55 cm	170 cm
18 cm	29 cm	70 cm	200 cm

Number-line – Create a cardboard number-line (about 6.5 x 81 cm long and labeled with numbers from 5 to 25). Punch a hole under each number and hang a slightly unbent paperclip in the hole. These will be used to hang the pendulums in part 2.

T-chart: label columns and fill in string lengths, students will fill in number of swings based on their results (for part 2)

length	# swings
200 cm	
170 cm	
120 cm	
etc.	

Data sheets – one per pair of students (or one for each student if you want them all to write).

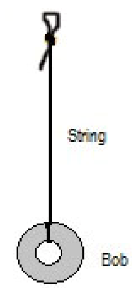
PROCEDURE

PART 1 – The Standard Pendulum *(40-50 min)*		
	For each pair of students you need: 1- pencil 1 -meter stick or tape measure 1 -50 cm string 1- metal washer (bob) 2-3- small pieces of tape 1- pair of scissors	*Teacher needs:* stopwatch or clock with second hand masking tape to supply to students at appropriate times pendulum to show students how to put together chart paper

Introduction: Doing experiments

1) We will be doing a series of investigations to learn how to design and conduct scientific experiments. We will study variables, do experiments and record data and look at our results.
2) We will work in pairs

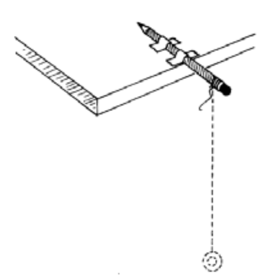
Introduce and make pendulums (at least 10-15 min)



1) First we have to make some equipment for our experiment
2) Have each pair of students make basic pendulums with string length of 38 cm
   a) Pass out 50 cm lengths of string and one washer to each pair of students
   b) Instruct students to tie one washer onto one end of the string (a double knot). Measure 38 cm to the other end of the string and form a 1-2 cm loop (big enough for the eraser end of a pencil to be inserted into the loop). The loop can be made either by tying a knot or using a small piece of masking tape. This loop is how you will hang your pendulum. It is important that the length of the string (from the top of the washer to the end of the loop) be 38 cm.
3) Be careful, students like to swing pendulums over their heads, this is not a safe activity and should not be allowed!

Exploring Pendulums (20min)

1) Introduce the pendulum: Have students look at the pendulums they have just made and think about what they do. Define a pendulum as a mass attached to a string that can swing back and forth.
2) Pose these questions to the students: How many times do you think a pendulum will swing back and forth in 15 seconds? How can we find out? *(At this point you can consider a more open inquiry procedure, or proceed with the guided-inquiry approach below.).*
3) Explain procedure
   a) We will explore how the pendulum swings. Teacher will be the timer and students will silently count full swings
   b) Set up pendulums
      i. Students will suspend the pendulums by attaching them to a pivot point – the pencil
      ii. pass out one or two 25 cm strips of tape to each pair
      iii. have students tape pencils to desk securely with end sticking out a few centimeters (at least an inch)
      iv. hang pendulum loop over the pencil so that it hangs freely



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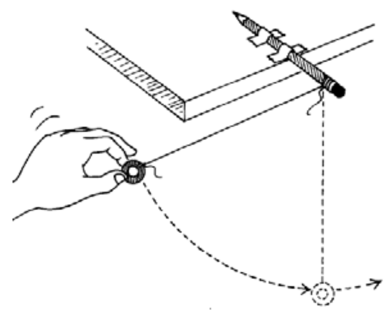
c) Practice start: ready set go – Is everyone doing the same thing? Give them a chance to figure out what needs to be done to standardize the pendulum test. They should all start at the same height or angle of the drop (straight out to the side, 90°), and they should all know what they are counting (one full cycle – back and forth)

d) Demonstrate and have students practice
e) Conduct the test:
i. at your signal, students release the pendulum and begin silently counting, at 15 seconds say stop.
ii. repeat
iii. have students report their counts – they should be around 12, but there may be some variation
f) Record results on student data sheets and on board for future reference.
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<tr><td colspan="2">Introduce concept and definition of variable (10 min)</td></tr>
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1) Brainstorm: based on their observations in part 1, have students think of things in the pendulum system that might affect, or change, the number of swings the pendulum makes in 15 seconds (be sure they suggest angle or height of release, mass/weight of bob, length of string). There are no right or wrong ideas here, just possibilities.
2) Introduce the concept and definition of variable: anything that you can change in an experiment that might affect the outcome.
3) Write out the term variable on the board and have students say it. Tell students that next time they will be investigating some of the variables by doing experiments with their pendulums.
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<tr><td colspan="2">Wrap up</td></tr>
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1) Start a word bank with the key terms. Ask students to suggest words. Be sure that variable, pendulum and cycle are included.
2) Start a chart to summarize knowledge gained through the investigation. Stimulate responses with questions such as: What is a pendulum? Where else have you seen pendulums? What is a variable? What variables can we test in our pendulums that might affect the number of cycles it makes in 15 seconds?
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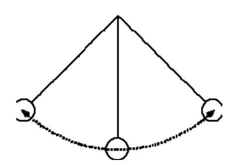
PART 2: Testing Variables -- Experiments to study the effect of angle of release, bob mass and string length on the pendulum. *(50 min over one or several days)*

For each pair of students you need:	*Teacher needs:*
pendulum from part 1 1- pencil (taped to desk) 1- meter stick or tape measure 2- additional metal washers or weights 2- small pieces of tape 2- new strings, different lengths * Data sheets	stopwatch or clock with second hand number line and T-chart* chart paper *see instructions in materials to prepare ahead)

Introduction

- Revisit the definition of variables and recall variables that might affect the number of times the pendulum swings in 15 seconds (be sure bob mass, angle of release, and string length are on the list).
- We can do experiments to explore how these variables affect the swinging of the pendulum. An experiment is an investigation to find out how variables affect outcomes. By changing one thing at a time, we can figure out the effect of that thing on our system.
- Review the pendulum system they used last time – this will be the standard to use for comparison in their next experiments. In this system we are measuring the number of cycles or swings the pendulum makes in 15 seconds. For our experiments we will examine how the height/angle of release, the mass of the bob and the length of the string affect the number of cycles or swings the pendulum makes in 15 seconds.

Question: How does the variable **height or angle of release** affect the number of swings?



1) Recall the number of swings in 15 seconds from earlier trials.
2) Ask students how they think releasing the pendulum from a 45° angle might change the number of cycles in 15 seconds? More swings? Fewer? Same?
3) Have students write down their predictions on the handout.
4) When everyone is ready, you, the teacher, will time for the class as they silently count the number of cycles in 15 seconds. Record results on data sheet. Repeat.
5) Compare with results from first part. (Results should be the same as when dropped from straight out (90°)).

Question: How does adding **mass** (weight) to the pendulum bob affect the number of swings in 15 seconds?

1) Ask students how they could find out if changing the mass (weight) of the bob will change the number of swings. Provide a second washer to use to increase the mass of the bob. They can add the second washer to their pendulum by either retying it or by threading the string through the hole in the additional washer (the first washer will hold the second washer on the string).
2) Next ask what they think the effect of adding more mass will be on the number of swings… More swings? Fewer? Same?
3) Have students write down their predictions on the data sheet.
4) When everyone is ready, keep time for the class as they count the number of swings in 15 seconds. Record results on data sheet. Repeat.
5) Compare with results from first part. (Results should be the same as those for smaller mass).

Question: How does **length of the string** affect the number of swings in 15 seconds?

1) Put up number line and T-chart
2) Tell the students they will next make pendulums with different length strings, but first they need to make a group record of the results from the first, standard pendulum trials. Have students tape their original 38 cm pendulums on the number line under the number representing the number of cycles it swung in 15 seconds in the original trial (should be around 12, but there may be some variation because all the strings may not be the same length or because of miscounts, but most will be close to 12)
3) Assign students pairs one of these pendulum lengths (these are FINISHED lengths) and pass out appropriate precut strings.

13 cm	20 cm	33 cm	90 cm
15 cm	22 cm	45 cm	120 cm
17 cm	25 cm	55 cm	170 cm
18 cm	29 cm	70 cm	200 cm

4) Students then make new pendulums in the same way they made their first pendulum.
5) Students will have to find a suitable place to hang their new pendulums. Some may be too long for hanging off of the desk or table. Make sure students do this in a safe manner. Have students do a test run to be sure the pendulums swing freely.
6) Next have students make a prediction about how they think the new length will change the number of cycles and record it on their data sheet.
7) When everyone is ready, teacher times for 15 seconds and students silently count the number of cycles. Repeat two more times.
8) Have students record their results on the T-chart and their data sheets.
9) Have students hang their pendulum on the number-line hook corresponding to the average number of swings it made in 15 seconds.
10) The number-line should show a smooth curve, with longer pendulums swinging fewer times and shorter swinging more, but there may be some pendulums that do not fit the pattern. Ask the students if they want to retest any of the pendulums.
11) Examine the pattern by studying the display– is there a relationship between the variables? what is the relationship between the length of the pendulum and the number of cycles in 15 seconds?
12) Help students to verbally describe the relationship in different ways. "If we make the string longer the number of cycles __________(increases? decreases?)" "If we make the string shorter, the number of cycles __________(increases? decreases?"). And leading to something like " the longer the string, the fewer the swings", or – "we see more swings with a shorter pendulum".
13) Have students make a drawing of the number-line or just keep it up to use in Part 3.

Wrap up

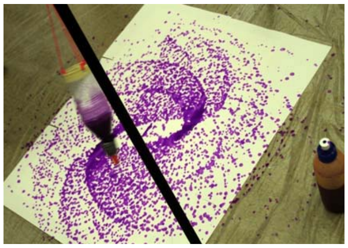
Update word bank (standard, controlled experiment) and knowledge chart (variables that did affect the number of cycles, variables that did not affect the number of cycles, etc.) and discuss. Were they surprised by the results? Do they have any new questions?

PART 3: Using graphs to make predictions *(40-50 min)*		
	For each pair of students you will need: graph sheets string washer pencil tape	*Teacher needs:* stopwatch or clock with second hand number line chart paper
Introduction		
	1) Review the number line and the relationships between the length of the pendulum string and the number of cycles in 15 seconds. 2) Introduce two-coordinate graphs. These are useful for plotting the results of experiments in which a variable was manipulated (the independent variable -in this case the length of the string, or mass, or drop angle) and the effect on a second variable (the response or dependent variable , in this case the number of swings in 15 seconds) is measured. The independent variable goes on the x-axis and the dependent variable goes on the y-axis.	
Making graphs		
	1) Help students to create graphs of the results from the string length experiment using the data on the T-chart. Model how to read the axes and plot the points on the board and then have students plot the data on their own graph sheets. 2) Once the graphs are completed, model how to draw a line through the points and have the students do the same.	
Using graphs to make predictions		
	1) Define prediction: an estimate based on information or experience 2) Pose a question: can you predict how many swings a pendulum with an 80 cm string will make in 15 seconds? Give students a chance to work on the question and then show them how to use the graph to find the answer – find 80 on the x-axis and follow a vertical line up to the line you drew. Then trace back horizontally to the y-axis to find the number of swings. 3) Give students some other string lengths to practice predicting the number of swings by using the graph.	
Testing new predictions		
	Pass out new lengths of strings, washers, pencils and tape to each pair of students and have them make a new pendulum. Have students use the graph to predict the number of swings their new pendulum will make in 15 seconds and then test them.	
Wrap up		
	Update word bank (two-coordinate graph, prediction) and knowledge chart (using graphs of past results to make predictions) and discuss.	

EXTENSIONS

1) Playing with Pendulums

- Tetherball – *what happens as the rope wraps around the pole? Make a mini tetherball by putting a tennis ball in a sock. It can be hit with a small racket*
- Pendulum bowling -- *Have students create a pendulum from string and a mass that could be used to knock something over, such as empty plastic beverage bottles, blocks,or domino tiles. Have students test their designs and determine the best place to position their pendulum for the most accurate collision with the objects.*
- Paint with a pendulum -- *Cut the bottom off a plastic soda or water bottle and screw a cap from a glue bottle on in place of the lid. Suspend the bottle from a tripod and center it over a large sheet of paper. Fill the bottle with thin paint and set the pendulum in motion. The design of the pendulum will be tracked from the falling paint on the floor. The motion creates a symmetrical splatter. Try the project several times with different swinging speeds and rope lengths, graphing the results. This is a great way to visualize the movement of a pendulum.*



2) Visualizing the path of a pendulum in a different way by painting with a with a pendulum

3) Scavenger hunt -- Look for pendulums outside, around the classroom, at home and in the community (amusement parks, construction sites, play ground)

4) Invent or design something using a pendulum – amusement park ride, better swing (higher, faster), a game, a seismograph, a necklace, other?

5) Design a pendulum clock -- have students figure out a chain length that makes the pendulum swing exactly 60 times per minute. How would this be useful? (Answer: If each swing took one second, a pendulum swing could be used as a regular clock.)

6) Study a metronome – what happens when the sliding mass is moved up or down on the arm? This changes the length of the pendulum arm – and the cycle should be longest when it is at the very end, and shorter when it is close to the bottom of the arm. Compare the number of cycles in 15 seconds to what you found with the string and washer pendulums of similar lengths? Can you use one to predict the other?

7) Compare the physics of a pendulum to a u-shaped ramp and a rolling marble or hot wheels track and car (gravity and inertia drive both of them, but in one the string holds the moving object, and the track holds it on the other; also think about how kinetic and potential energy change as the bob or car move)

8) Further thought:

- Pendulums in space? How would pendulums behave on the moon (slower because of less gravity). How about at the International Space Station? (would not swing due to absence of gravity). Could you test these ideas?
- Pendulums under water? Do pendulums work underwater? What is different? (Much more resistance)
- If you have a pendulum 15 cm. long and your friend has one 25 cm. long, whose pendulum will swing more times in 30 seconds? (yours).
- If a pendulum clock was running slow, how could you help to correct it? (Make it swing faster by shortening the length of the pendulum).
- If a heavy person and a light person both start to swing on a swing in a park at the same time, will they swing with the same frequency? (Yes because mass does not affect the number of swings per unit time).
- If you are swinging from an overhead bar, how could you increase your frequency of swings? (Shorten your length, by drawing your legs up to your stomach).