

# PENDULUMS and LAWS OF NATURE

## TEACHER GUIDE

### *Pendulums: Does nature always obey rules?*

**GRADES:** 8–12

#### STANDARDS ALIGNMENT

This lab can be an enrichment activity for advanced Physical Science or Algebra I students or a scaffolded introductory activity for AP Physics students. This activity should be at grade-level for Honors/Standard Physics as written, and including the calculus-based introductory activity puts this activity at grade-level for AP Physics or higher-level mathematics courses.

**OVERVIEW:** After viewing the **Pendulums and Laws of Nature Lesson Video** found on the [Lesson webpage](#), students will explore the meaning of laws of nature. This lab differs from a traditional STEM lab in that students are asked to engage in deep reflection about the scientific process and the behavior of the natural world.

**TIME REQUIRED:** Two to three class periods (100-150 minutes)

#### **SUGGESTED LESSON FLOW:**

##### **Day 1:**

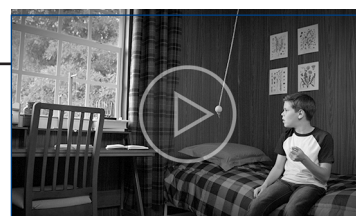
1. As a class, students view the 8-minute video found on the [Lesson webpage](#).
2. Students should read the short [Lesson Introduction](#) document before they begin the activity.
3. Begin the [Pendulums and Laws of Nature Lesson Student Worksheet](#).

##### **Day 2:**

1. Finish the Pendulums and Laws of Nature Lesson Student Worksheet.
2. Review lab results as a whole class.
3. Quiet time for reflection and for students to individually jot down their thoughts on each of the questions in their student worksheets.
4. Review the [Establishing Group Norms for Discussion](#) as a class (the [Bok Center for Teaching and Learning](#) has some helpful resources).
5. Classroom discussion of the reflection questions.

##### **If time allows or at home:**

Students compose a written reflection following the instructions at the end of their Simple Pendulum Lesson Student Worksheet.



#### **NOTE**

If your class has recently implemented a Searching Lesson, you can skip the video introduction and begin the video at minute 03:45.

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**SET-UP:**

Students should ideally be placed in groups of 2-3. Each lab group will need one set of the materials listed below:

**NOTE**

Educational supply companies often sell kits labeled under the name "Pendulum Investigation" or "Pendulum Lab Kit" which contain all the necessary supplies.

- **Lab stand with clamp**  
If you do not have access to lab stands, students can tie their pendulums to any support, so long as the pendulums are allowed to swing freely.
- **String**  
Students should receive pre-cut (or be instructed to cut) strings of multiple lengths, such that they are able to create pendulums of 10, 30, and 50 cm. For each trial, they should leave extra string with which to tie off their pendulum so that its total length, once hanging, matches the length in the table. Alternatively, students may be provided with one long string which they can measure and tie off at the appropriate length for each trial.
- **Bob or other small weight (washer, large bead, etc.)**  
For an extension activity, have students vary the mass of the bob and time the pendulum's swings again to determine the relationship between mass and period. Students who have not studied conservation of energy are often surprised that mass has no effect on period. This can be easily done by tying on more washers/beads.
- **Meter stick or ruler**
- **Stopwatch**
- **Line of best fit ruler** (optional)
- **Excel** (optional)

**SAFETY PRECAUTIONS:**

1. Lab equipment can be a trip hazard. Ensure stands, strings, and bobs are contained and out of the way.
2. Handle clamps and scissors carefully to avoid pinching or cutting skin.
3. Ensure that pendulums are securely mounted so they will not collapse or tip over.

**BEFORE YOU START:**

1. Ensure each group has the necessary supplies.
2. Demonstrate proper lab set-up and data collection.

**USEFUL BACKGROUND READINGS FOR HUMANITIES-BASED IDEAS:**

- Chapter "**The Lawful Universe**" in *The Accidental Universe*, by Alan Lightman (New York: Vintage Books, 2013). [Discusses the concept of "laws of nature" and the history of that concept]
- Chapter "**Miracles**" in *Probable Impossibilities*, by Alan Lightman (New York: Vintage Books, 2021). [Discusses the nature of "miracles," which are phenomena that do not obey the laws of nature, and why many people believe in miracles]
- "**Where Science and Miracles Meet**," by Alan Lightman, *The Atlantic*, March 22, 2021. [Discusses the nature of miracles, which are phenomena that do not obey the laws of nature, their belief, and the position of science towards miracles]

# TIPS, TROUBLESHOOTING, AND SUGGESTED ANSWERS

## Worksheet Page 1

**STUDENT WORKSHEET**

### PENDULUMS and LAWS OF NATURE

**Pendulums: Does nature always obey rules?**  
*Investigating the Relationship Between Period and Length*

**INTRODUCTION**

Many systems in nature can be described by pendulums. Using Newton's Laws of Motion and calculus, it can be shown that in a pendulum small displacements from the equilibrium position follow the laws of simple harmonic motion – where the restoring force on an object is proportional to its displacement from equilibrium. In the Searching series video clip you just watched, Dr. Alan Lightman describes the satisfaction of testing this law himself. Today, you will perform the same experiment.

**OBJECTIVE**

In this lesson, you will collect and analyze data to determine the relationship between the length of a simple pendulum and its period of oscillation for small angles. After the lab, you'll reflect on your experimental process and explore the meaning of laws of nature.

**MATERIALS**

- Lab stand with clamp
- String
- Bob or other small weight (washer, large bead, etc.)
- Meter stick or ruler
- Stopwatch
- Line of best fit ruler (optional)
- Excel (optional)

**PROCEDURE**

1. **Set up the pendulum.**
  - a. Attach the bob to the end of the shortest string.
  - b. Hang the string from the clamp on the lab stand, ensuring the pendulum can swing freely.
  - c. Measure the string from clamp to bob. Record the length in the table below.
2. **Prepare the first trial.**
  - a. Using the protractor to measure, pull the pendulum back a small amount from the vertical. Keep the string taut.
3. **Complete the first trial.**
  - a. Release the pendulum and start timing with the stopwatch. Let the pendulum complete 4 full swings before stopping the timer.
4. **Record the result.**
  - a. Record the trial time and divide by 4 to calculate the period (T) of a single swing. Record the period in the table below.
5. **Complete two more trials with the same length of string.** Record your data in the table below.
6. **Repeat steps 1-5 with each string.**

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Teachers may choose to run the Lesson without providing the step-by-step procedure for the students. Instead, they may give students a question to answer and a list of materials they can use to answer it.

For the law of simple harmonic motion to apply, ensure students only pull back their pendulums to small angles (less than 45 degrees). For an extension activity in higher-grade math and physics courses, guide students through a discussion of the Taylor Series expansion of sine to discover the small angle approximation.

Clarify that one full swing implies that the bob is back at its release position ("down and back"). Using an average of 4 swings instead of attempting to time a single swing reduces error.

Have students all follow the same rounding convention.

# TIPS, TROUBLESHOOTING, AND SUGGESTED ANSWERS

## Worksheet Page 2

If time allows, have students repeat the procedure and record data for more lengths. More data points will produce a clearer trend.

STUDENT WORKSHEET

PENDULUMS and LAWS OF NATURE

DATA

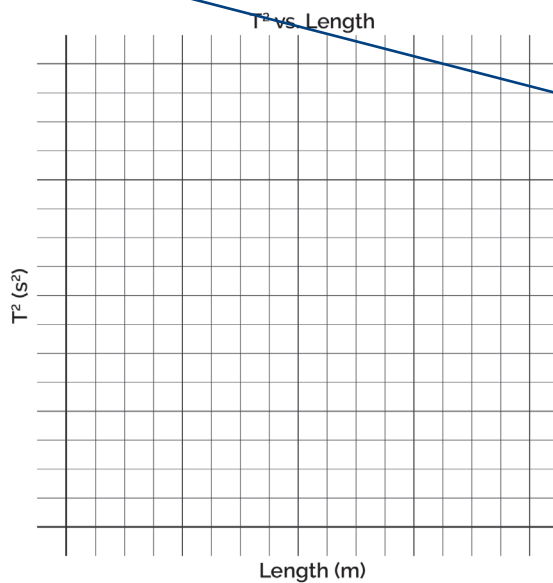
Length (m)	Trial 1 Period (s)	Trial 2 Period (s)	Trial 3 Period (s)	Average (s)	T <sup>2</sup> (s <sup>2</sup> )
0.10					
0.30					
0.50					

ANALYZE DATA

Graph

1. Plot the square of the period vs. the length for each string on the graph below.
2. Using a line of best fit ruler, draw a trendline through the points on your graph below. Calculate the equation for the line. Trendline equation: \_\_\_\_\_

You may choose to have students create their plot using a computer graphing tool like Excel to produce a true line of best fit. Students can also use a linear regression calculator tool to find the line of best fit. Graphing and drawing a good trendline by hand, however, should also produce the desired result.



Plotting T<sup>2</sup> vs. length will produce a linear function instead of a square root function.

If students drew a trendline by hand, remind them how to find the equation of their trendline: Pick two clear points on the line, use the slope formula  $\frac{(y_2 - y_1)}{(x_2 - x_1)}$  to find the slope, and plug in the slope along with a clear point into slope-intercept form to find *b*. Alternatively, they can substitute into point-slope form and convert into slope-intercept form.

# TIPS, TROUBLESHOOTING, AND SUGGESTED ANSWERS

## Worksheet Page 3

Treating length as the independent variable and the square of the period as the dependent variable, students should find  $\frac{4\pi^2}{g}$  approximately as the slope of their graph and 0 as their y-intercept. After the class has had time to discover this relationship for themselves, make sure to walk struggling students through squaring both sides of the equation and comparing it to a linear relation in slope-intercept form with  $l$  as the independent variable.

The conclusion on this page should be formatted like a typical lab report conclusion section. Encourage students to be as specific as possible without generating truth statements for which they have no proof.

STUDENT WORKSHEET

PENDULUMS and LAWS OF NATURE

Analyze

The mathematical relationship between the period and the length of a pendulum is given by:

$$T = 2\pi\sqrt{(L/g)}$$

1. Determine the theoretical slope for the graph above. Show your work in the space below.
2. Calculate the percent error between the theoretical value for the slope of the line of best fit and your experimental value for the slope of the trendline you drew. Show your work in the space below.

CONCLUDE AND REFLECT

Conclusion

In the space below, write a paragraph conclusion which includes the following elements:

1. Your experimental result
2. The mathematical relationship between pendulum length and period
3. Your percent error and possible sources of error
4. Your prediction about the relationship between other variables (i.e. mass, initial angle) and period

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Provide students with the percent error formula if necessary:

**Percent error =  $\frac{\text{experimental value} - \text{theoretical value}}{\text{theoretical value}} \times 100$**

Make a class table of results and percent errors on the board, separated by lab group. Discuss with the whole class how the results are similar and what could have introduced error.

# TIPS, TROUBLESHOOTING, AND SUGGESTED ANSWERS

## Worksheet Page 4

### STUDENT WORKSHEET

### PENDULUMS and LAWS OF NATURE

#### *Reflection*

Using the questions below to guide your thoughts, reflect upon your experience during this lab. Jot down any thoughts in the space below and prepare to share your thoughts in a group discussion.

1. What have you learned about the behavior of nature from this activity?
2. Do you think all physical phenomena in nature obey laws?
3. What do you think would happen if some natural phenomena did not obey laws?
4. How do laws of nature allow us to make predictions about physical phenomena?
5. Do you think that everything in nature follows laws of "cause and effect" – that is – every event that happens was caused by a previous event?

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The reflection section on this page is meant to encourage students to make connections between the scientific process and the nature of the universe. Students (and teachers!) may be uncomfortable with some of these questions or with sharing their thoughts on these questions aloud. Have a dedicated time set aside after students have compared their lab results and written their conclusions to reflect quietly on these questions.

Before you begin the classroom discussion, have the group set norms for discussion. See [Establishing Group Norms for Discussion](#) for ideas on norm-setting before group discussions. After the group discussion portion, if time allows, have students each choose one or two questions and produce a written reflection. Students can work on their reflections at home and submit them later.

# TIPS, TROUBLESHOOTING, AND SUGGESTED ANSWERS

## Worksheet Page 5

STUDENT WORKSHEET

PENDULUMS and LAWS OF NATURE

### WORKSHEET FOR CALCULUS-BASED PHYSICS COURSES (Optional)

INTRODUCTION

A simple pendulum is a small mass suspended from a light, rigid rod. Ideally the mass will be small enough so that it will not deform the rod, but the rod should be light so that we can neglect its mass. In this lab, we will create a pendulum using a small mass bob and lightweight string. If we displace the bob slightly and let it go, the pendulum will start swinging. We will assume that there is no friction. In this idealized situation, once the pendulum is started, it will never stop. The only force acting on the pendulum is the force of gravity.

In the space below, draw a free-body diagram representing the forces present on the pendulum bob at the position shown in Figure A. Write an expression for the sum of forces in the x-direction, perpendicular to the string.

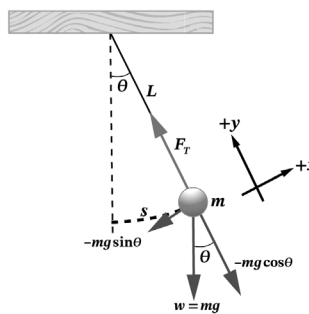
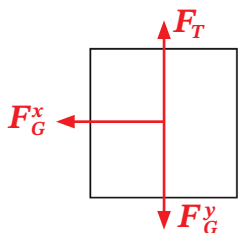


Figure A

$$F_{net}^x = F_G^x = -mg \sin \theta$$

Consider Newton's 2nd law,  $F_{net}^x = ma_x$  in the direction perpendicular to the string. Given the x-component of the force of gravity, our equation of motion for the pendulum is

$$\begin{aligned} -mg \sin \theta &= ma \\ -g \sin \theta &= a \end{aligned}$$

Given  $\frac{d^2\theta}{dt^2} = \frac{a}{L}$ , rewrite the equation of motion in terms of  $g$ ,  $L$ , and  $\theta$ .

$$\frac{d^2\theta}{dt^2} = -\frac{g}{L} \sin \theta$$

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# TIPS, TROUBLESHOOTING, AND SUGGESTED ANSWERS

## Worksheet Page 6

### STUDENT WORKSHEET

### PENDULUMS and LAWS OF NATURE

Worksheet for Calculus-based Physics Courses (Optional)

For small angles (less than 15 degrees),  $\sin\theta \approx \theta$ . Using the small angle approximation gives an approximate solution of this differential equation for small angles.

$$\frac{d^2\theta}{dt^2} = -\frac{g}{L}\theta$$

and

$$\frac{d^2\theta}{dt^2} + \frac{g}{L}\theta = 0$$

This is a "harmonic oscillator" equation. In the space below, verify that the solution to  $\frac{d^2\theta}{dt^2} + \frac{g}{L}\theta = 0$  is  $\theta = A\sin\left(\sqrt{\frac{g}{L}}t\right)$  where  $A$ , the amplitude, is a constant and the largest angle that the pendulum achieves in its swing, determined by the initial conditions.

Assume the solution to the differential equation is of the form

$$\theta(t) = A\sin(\omega t)$$

where  $A$  is amplitude and  $\omega$  is the angular frequency. The amplitude  $A$  is the largest angle the pendulum makes in its swing, determined by the initial conditions.

Then,

$$\frac{d^2\theta}{dt^2} = A\omega^2\sin(\omega t)$$

and our original equation becomes

$$-A\omega^2\sin(\omega t) + \frac{g}{L}A\sin(\omega t) = 0$$

$$A\sin(\omega t)\left(-\omega^2 + \frac{g}{L}\right) = 0$$

Assuming a non-trivial solution,

$$-\omega^2 + \frac{g}{L} = 0$$

$$\omega^2 = \frac{g}{L}$$

$$\omega = \sqrt{\frac{g}{L}}$$

Thus, the solution to our original equation is

$$\theta(t) = A\sin\left(\sqrt{\frac{g}{L}}t\right)$$

The time  $t$  for the pendulum to make one complete swing, called the period ( $T$ ), is found by setting  $\sqrt{\frac{g}{L}}t = 2\pi$ .

In the space below, solve for the period of one complete swing. This is the period equation of a simple pendulum.

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Image source: 15.5 Pendulums - Physics LibreTexts

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