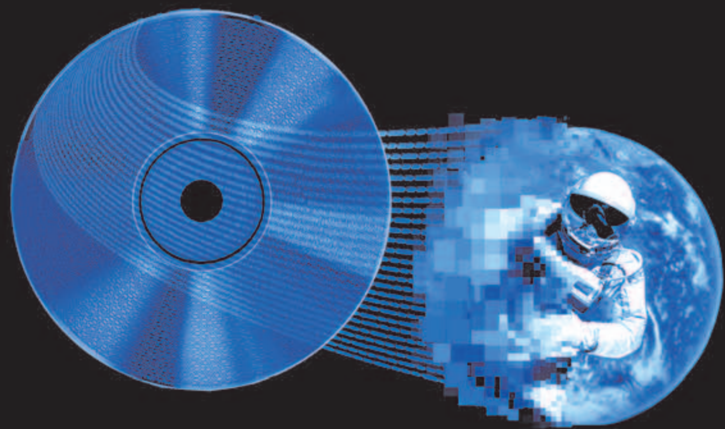
Foundations of Physics



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Teacher's Guide

First Edition
CPO Science
Peabody, Massachusetts 01960

cpo science

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12.3 Angular Momentum

Learning Goals	Reading Synopsis	Materials and Setup
• Observe how angular momentum tends to keep an object rotating at a constant angular speed. • Show that angular momentum depends on both the angular speed and the moment of inertia. **Key question:** How does the first law apply to rotational motion? **Leading questions:** • What is angular momentum? • How is angular momentum related to moment of inertia? • How do you calculate angular momentum? • Is angular momentum a vector like linear momentum? • How can the law of conservation of angular momentum be used to explain the motion of rotating objects?	Angular momentum is the rotational equivalent of linear momentum. The angular momentum of an object comes from the organized motion of each particle of mass around the center of rotation. Angular momentum obeys a conservation law similar to linear momentum. The angular momentum of an object can be changed by torques applied to the object. The angular momentum of an object is its moment of inertia multiplied by its angular velocity. The units of angular momentum are kg-m^2/sec. Angular momentum is a vector; however, the vector points along the axis of rotation and not in the direction of motion. If the angular momentum of a system is changed, the system exerts reaction torques acting in a direction to resist the change. A gyroscope is a device that uses angular momentum to maintain its orientation. **Sequence:** Students complete the reading after the Investigation.	• One flexible straw • String (about one meter long) • Two washers **Duration:** One class period

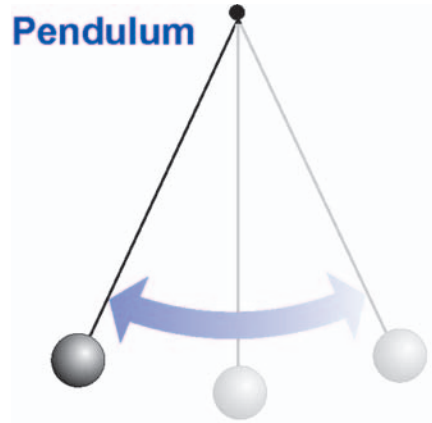
13.1 Harmonic Motion

Learning Goals	Reading Synopsis	Materials and Setup
• Measure the amplitude and period of a pendulum. • Describe any oscillator in terms of frequency, period, amplitude, and phase. • Learn to read and represent frequency, period, amplitude, and phase on a graph. **Key question:** How do we describe the back and forth motion of a pendulum? **Leading questions:** • How do we describe repetitive motion in physics? • What are some examples of harmonic motion and oscillators? • Why does a pendulum clock need to be wound?	There are two types of motion: linear and harmonic. Harmonic motion repeats itself over and over. A pendulum swinging back and forth is an example of harmonic motion. A cycle is a pattern of motion that repeats over and over. Harmonic motion is a sequence of repeating cycles. A system that exhibits harmonic motion is called an oscillator. A pendulum moving back and forth and a spring bouncing up and down are examples of oscillators. The period of an oscillator is the time it takes to complete one cycle. The frequency of an oscillator is the number of cycles it makes per second. The amplitude of a cycle is the maximum amount the system moves away from equilibrium. Damping is the reduction of amplitude over time due to friction. Harmonic motion graphs show cycles are usually drawn with time on the horizontal axis. Amplitude, period, and frequency can be determined easily from a graph of position versus time. The phase of an oscillator describes where the oscillator is in its cycle. **Sequence:** Students complete the reading after the Investigation.	• Pendulum (use at least 3 steel balls with string attached, two of which should be the same size) • Physics stand • Timer and one photogate, AC adapter (or 9-volt battery), and a cord to connect the photogate to the timer • Calculator • Graph paper **Duration:** One class period

13.1 Harmonic Motion

Key Question: How do we describe the back and forth motion of a pendulum?

Objects generally have two kinds of motion. Motion that goes from one place to another is called linear motion. We use words such as distance, time, speed, and acceleration to describe linear motion. The second kind of motion repeats itself over and over and is called harmonic motion. This Investigation introduces students to harmonic motion using a simple pendulum. The students determine which of three variables (length, mass, amplitude) have the greatest effect on the period of an oscillating pendulum. They apply their analysis to design a pendulum clock that measures 30 seconds. A double pendulum is then used to illustrate the concept of phase.



Reading Synopsis

Students read Section 13.1 Harmonic Motion after the Investigation.

There are two types of motion: linear and harmonic. Harmonic motion repeats itself over and over. A pendulum swinging back and forth is an example of harmonic motion. A cycle is a pattern of motion that repeats over and over. Harmonic motion is a sequence of repeating cycles.

A system that exhibits harmonic motion is called an oscillator. A pendulum moving back and forth and a spring bouncing up and down are examples of oscillators. The period of an oscillator is the time it takes to complete one cycle. The frequency of an oscillator is the number of cycles it makes per second. The amplitude of a cycle is the maximum amount the system moves away from equilibrium. Damping is the reduction of amplitude over time due to friction.

Harmonic motion graphs show cycles are usually drawn with time on the horizontal axis. Amplitude, period, and frequency can be determined easily from a graph of position versus time. The phase of an oscillator describes where the oscillator is in its cycle.

The Investigation

Leading Questions

- How do we describe repetitive motion in physics?
- What are some examples of harmonic motion and oscillators?
- Why does a pendulum clock need to be wound?

Learning Goals

By the end of the Investigation, students will be able to:

- Measure the amplitude and period of a pendulum.
- Describe any oscillator in terms of frequency, period, amplitude, and phase.
- Learn to read and represent frequency, period, amplitude, and phase on a graph.

Key Vocabulary

harmonic motion, oscillator, oscillation, period, frequency, hertz, amplitude, damping, periodic motion, hertz, phase, phase difference

Setup and Materials

Students work in groups of four or five at tables.

Each group should have:

- Pendulum (use at least 3 steel balls with string attached, two of which should be the same size)
- Physics stand
- Timer and one photogate, AC adapter (or 9-volt battery), and a cord to connect the photogate to the timer
- Calculator
- Graph paper

Details

Time One class period

Preparation Try out the experiment prior to the class to anticipate student problems and questions.

Assignments Section 13.1 Harmonic Motion in the **Student Edition** after the Investigation.

Skill Sheets 13.1 Harmonic Motion

Equipment Setup Pendulum

Teaching the Investigation

1 Introduction
2 The pendulum
3 Setting up the pendulum
4 Measuring the period
5 Variables that affect the period of a pendulum
6 Analyzing the data
7 Applying what you know
8 Phase

Introduction

Linear - one place to another, no repeats

Harmonic - back and forth, repeating

Objects generally have two kinds of motion. One kind of motion goes from one place to another and is called linear motion. Give me some examples of linear motion from the Investigations we have done so far.

A ball on a ramp (the translational aspect of the motion, that is), pulling down on a pulley string to raise a weight, and a projectile are some examples of motion that involves a movement from one place to another.

What characteristics of linear motion have we measured in our Investigations?

Distance, time, speed, and acceleration.

The second type of motion repeats itself over and over like a child moving back and forth on a swing. This type of motion is called harmonic motion. Give some examples of harmonic motion that you encounter on a daily basis.

The Earth's rotation, a pendulum, a swing, a heart beating, a clock ticking, a wheel spinning, and a ball rolling around and around as it moves down a ramp (the rotational aspect of the motion).

The pendulum

A pendulum is a good example of harmonic motion.

1 A pendulum is a good example of harmonic motion. Watch it move. How would you describe the motion? Imagine you are talking to someone on a cell phone a thousand miles away. You want to tell them exactly what the motion is doing. What do you say?

Prompt the class for descriptive words. "Back and forth," "repeating," "cycles," and "swinging" are common responses. Lead them to be very specific, such as how long or how wide the swing is. Introduce the terms cycle, period, and amplitude.

Setting up the pendulum

2 Now you should work in your group to set up your pendulum. Attach the pendulum hanger to the top hole of the physics stand. Use the medium-sized ball on the string as your pendulum. Loosen the post and slip the string through the hole in the center of the post.

As groups set up their pendulums, remind the students that the post does not unscrew all the way off. They should loosen the post just enough to expose the hole for the string to go through. The post should then be gently tightened enough to hold the string. Over-tightening the post will damage the string.

Cycle - The cycle is the repeating unit of motion.

Because harmonic motion is so important, we have words to describe it so everyone can be clear about exactly what is happening. These words are different from the words we use to describe linear motion (distance, speed, acceleration). The **cycle** is one complete part of the motion. The whole motion is one cycle after another. That means the cycle has to include all of the motion. For the pendulum, if we start counting the cycle here, the cycle ends here, when the pendulum has come all the way back again. You can count cycles, one, two, three, etc.

Use your finger to point to the start of a cycle as the pendulum swings all the way to one side. The cycle ends when the pendulum has returned to the same place again. Have the students swing their pendulums and practice counting cycles, just so they get used to the definition of a cycle.

Measuring the period

Period - The period is the time it takes to make one complete cycle.

The **period** of a pendulum is the time it takes to make one complete cycle. Faster pendulums have short periods. Slow pendulums have long periods. You can define a period for all harmonic motion. Can anyone tell me the period Earth's rotation? How about the period of a heartbeat?

Prompt a discussion of period and cycles. The period of the rotation of Earth is one day and a heartbeat is about one second.

To measure the period, we can use the photogates. Use one of the threaded knobs to attach a photogate to the stand so that the pendulum ball breaks the light beam as it swings through.

13.1 Harmonic Motion

Question: How do we describe the back-and-forth motion of a pendulum?

In this Investigation, you will:

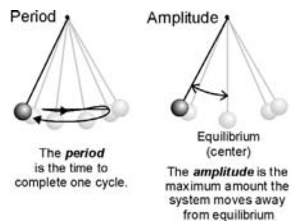
1. Measure the amplitude and period of a pendulum.
2. Determine how to change the properties of a pendulum.
3. Learn to read and represent frequency, period, amplitude, and phase on a graph.

Objects generally have two kinds of motion. One kind of motion goes from one place to another like a person walking from home to school. This is *linear motion*. We use words such as distance, time, speed, and acceleration to describe linear motion. The second kind of motion repeats itself over and over like a child going back and forth on a swing. This kind of motion is called *harmonic motion*. The word *harmonic* comes from the word *harmony* meaning "multiples of." Any system that exhibits harmonic motion is called an *oscillator*.

1 The pendulum

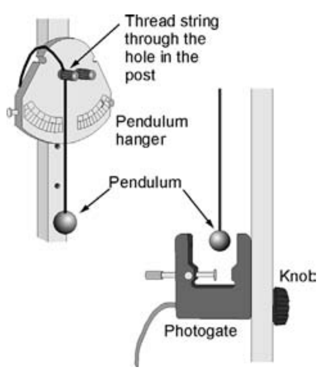
A pendulum is an oscillator made from a mass on a string. The mass is free to swing back and forth.

- A *cycle* is one complete back-and-forth motion.
- The *period* is the time it takes to complete one full cycle. The period of a pendulum is the time it takes for the pendulum to swing from left to right and back again.
- The *amplitude* describes the size of the cycle. The amplitude of a pendulum is the amount the pendulum swings away from equilibrium.

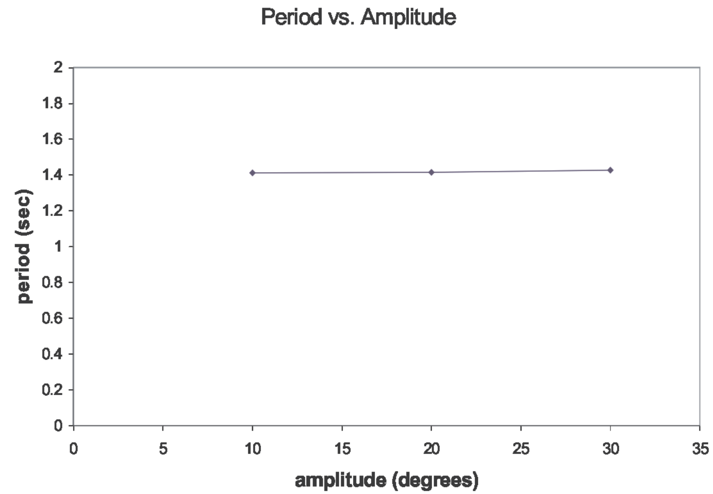


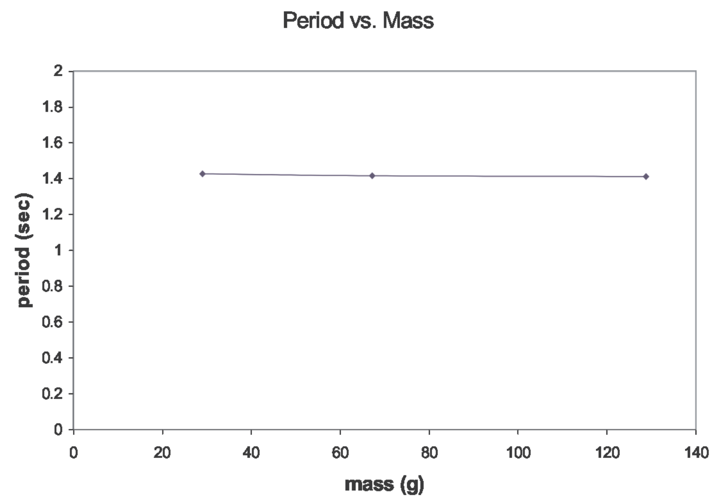
2 Setting up the pendulum

1. Attach the pendulum hanger to the top hole in the physics stand.
2. You will use the medium-sized ball on the string as your pendulum. Loosen the post and slip the string through the hole in the center of the post. Note: The post does NOT unscrew all the way off. Loosen it just enough to expose the hole for the string to go through. Gently tighten the post to hold the string. DO NOT tighten the post too tight or you will damage the string. It takes very little pressure to hold it.
3. Use one of the threaded knobs to attach a photogate to the stand so that the pendulum ball breaks the light beam as it swings through. You may need to adjust the leveling feet on the stand to make the ball swing through the center of the photogate. It does not matter if the pole is not exactly vertical.



4 Graphs from question 4b:





Variables that affect the period of a pendulum

Set the timer on "period."

The pendulum breaks the light beam on the photogate twice in each cycle.

In period mode, the time measures the time interval between one break of light and the next.

3

It is somewhat tricky to get the pendulum to swing through the photogate without hitting it. You have to release the ball with no twisting. The best way to release the ball is to stand to one side and carefully release it with two fingers.

Demonstrate how to get the pendulum swinging without hitting the photogate. Circulate to each group and help them develop a good technique.

Set the timer on "period." When the pendulum swings through the light beam, the timer measures the period. It takes a few swings to make the measurement. If you hit the reset button once, it freezes the display so you can write down the number. If you hit reset a second time, the timer starts back at zero.

Circulate around the class and help students use the timer to measure the period.

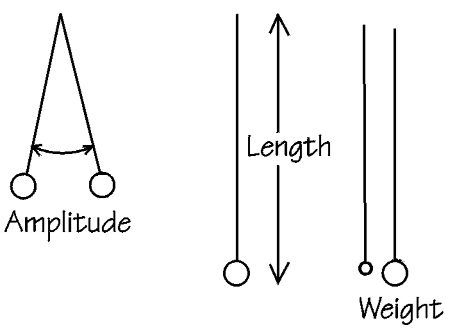
Watch the pendulum. How many times does it pass the light beam in one cycle?

Prompt the class to observe and notice that the pendulum breaks the beam twice in each cycle, once moving to the left and once moving to the right.

The timer measures the period of whatever is breaking the light beam. It does not know that you have a pendulum. How do we get the true period of the pendulum from the measurement on the timer?

Help the students see that the period of the pendulum is twice the time indicated on the timer. The timer in period mode measures the time interval between one break of the light beam and the next. This time interval is only half the period of a pendulum because a pendulum swings through the photogate twice on each cycle

Analyzing the data



String length is the most important variable.

A larger amplitude raises the pendulum higher above the lowest point so there is more potential energy at the start so the speed is higher.

Weight had little affect because more force is compensated by additional inertia due to greater mass.

4

What did you discover about the three variables? Which one had the greatest effect?

Discuss results with the class. Everyone should have discovered that the string length was the most important variable. Mass and amplitude made some difference but not much compared with changing the length of the string.

Why do you think the mass of the ball did not have much of an effect?

Students should recall that under the acceleration of gravity, the effect of more weight (force) is compensated by the additional inertia due to the increase in mass. The pendulum is another example of heavier and lighter objects accelerating at the same rate under the influence of gravity.

Why do you think making the amplitude larger did not make more of a difference? You increased the distance the pendulum had to swing by three times, or 300 percent! Usually traveling a longer distance takes more time, so the period should have gotten much longer. Think about energy and the roller coaster.

A larger amplitude raises the pendulum higher above the lowest point. That means there is more potential energy at the start. This gets converted to more kinetic energy, giving a higher speed. The higher speed almost exactly compensates for the larger distance, leaving the period almost unchanged. There is a slight change of period with amplitude, however, and it is not an experimental error.

Take your data and make a graph for each of the three variables. You want to show the effect on the period. How should you set up the graphs? The scale of your graph is important. You can be fooled by graphs that seem to show big changes because the scales are different. For example, suppose the period changed from 1 second to 1.05 seconds as I decreased the mass from 129 g washers to 28 g. When the vertical scale goes from 1.0 to 1.1 the change it looks like a lot. If the scale goes from zero to 1.5, the change looks very small. When comparing graphs, they all should have the same scale.

Have students make their graphs. If time allows, have them share their graphs with the class.

3 The three pendulum variables

In this experiment, the period of the pendulum is the dependent variable. There are three independent variables: the mass, the amplitude of the swing, and the length of the string.

1. Put the Timer in period mode and attach the photogate to input A. When the A light is on, the display shows the period defined by successive breaks in the light beam as the pendulum swings through. The red (O) button resets the Timer to zero. It takes a few swings for the Timer to make the measurement.
2. The Timer in period mode measures the time interval between one break of the light beam and the next. This time interval is only half the period of a pendulum because a pendulum swings through the photogate *twice* on each cycle. To determine the period of the pendulum, multiply the Timer reading by two. Record your information in Table 1.
3. The length of the string can be changed by sliding it through the hole in the post. Measure the length from the underside of the post to the center of the steel ball. Put your data in column 3.
4. Change the mass by using one of the other sizes of steel balls.
5. The amplitude can be changed by varying the angle that the pendulum swings.

Design an experiment to determine which of the three variables has the greatest effect on the period of the pendulum. Your experiment should provide enough data to show that one of the three variables has much greater an effect than the other two. Be sure to use a technique that gives you consistent results.

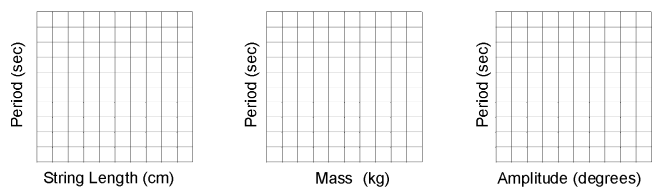
Table 1: Period, amplitude, mass, and length data

Mass (g)	Amplitude (degrees)	String length (cm)	Time from Timer (seconds)	Period of pendulum (seconds)

4 Analyzing the data

a. Of the three things you can change (length, mass, and angle), which one has the biggest effect on the pendulum, and why? In your answer, you should consider how gravity accelerates objects of different mass.

b. Split up your data so that you can look at the effect of each variable by making a separate graph showing how each one affects the period. To make comparison easier, make sure all the graphs have the same scale on the y-axis (period). The graphs should be labeled as shown in the example below:



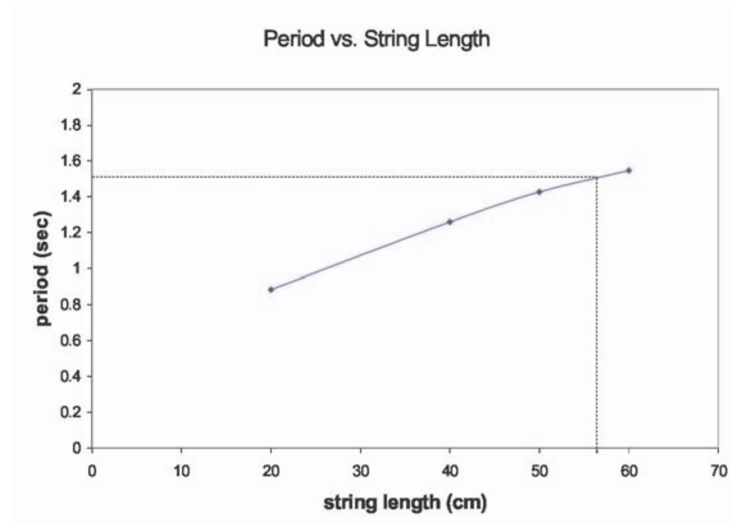
3 4 Example answers

Table 1: *Period, amplitude, mass, and length data*

Mass (g)	Amplitude (degrees)	String length (cm)	Time from timer (seconds)	Period of pendulum (seconds)
29.0	10	50	0.7144	1.428
67.2	10	50	0.7085	1.417
128.8	10	50	0.7067	1.413
29.0	20	50	0.7079	1.415
29.0	30	50	0.7142	1.428
29.0	10	20	0.4420	.8840
29.0	10	40	0.6295	1.259
29.0	10	60	0.7734	1.547

4a. insert answer

4b. Additional graph:



Applying what you know

Design problem: create a clock that measures a time interval of 30 seconds.

5

I have a design problem for you. You are to create a clock and your clock must measure a time interval of 30 seconds. That means you need to say "start" and then "stop" as close as possible to 30 seconds later. Your clock needs to work by counting cycles of a pendulum. This is how grandfather clocks work. The minute and hour hands are really just counters for the pendulum.

To start, figure a basic design. How many cycles do you want to be equal to 30 seconds? Will your pendulum swing that long? Is there a way to make it swing longer without slowing down as much?

Circulate and help the students pick designs. More mass means more energy storage for a given amplitude, so the pendulum swings longer. A longer period helps too since you don't have to count as many cycles. A successful design might be 20 cycles of a pendulum with a 1.5 second period, or 30 cycles of a pendulum with a 1 second period. When each group is ready, visit their table and use the timer as a stopwatch to test their clock. They have to tell you "1, 2, 3, start" and then "stop" when they have counted the requisite number of periods. Most groups will get between 29 and 31 seconds, and it is not uncommon to have times between 29.7 and 30.3 seconds, which is less than 1 percent error! You may choose to grade the experiment on the percent error.

Phase

Set up a dual pendulum.

See if you can make the dual pendulums swing in phase, the out of phase by 180 degrees.

6

Phase is another important concept to understand when comparing one oscillator to another. Set up a dual pendulum as shown in the diagram in Part 6 of the Investigation. The strings wrap over and around the side pegs. The two pendulums will swing alongside the pole as shown.

Demonstrate how to set up a dual pendulum.

Start with equal string lengths. See if you can make the dual pendulums swing in phase, and then out of phase by 180 degrees (one-half cycle). Next, set the pendulum strings to different lengths. Start them in phase and see what happens to the phase as they keep swinging. See if you can construct a pair of pendulums where one has twice the period of the other.

This is a great opportunity for students to explore examples of in-phase and out-of-phase oscillators. This will support students' understanding of sound and light wave constructive and destructive interference in future Investigations.

5 Applying what you know

Pendulum clocks were once among the most common ways to keep time. You can still buy beautifully made contemporary pendulum clocks. To make a pendulum clock accurate, the period must be set so that a certain number of periods equals a convenient measure of time. For example, you could design a clock with a pendulum that has a period of 1 second. The gears in the clock mechanism would then have to turn the second hand 1/60th of a turn per swing of the pendulum.

a. Using your data, design and construct a pendulum that you can use to accurately measure a time interval of 30 seconds. Test your pendulum clock against the Timer set to stopwatch mode.

b. Mark on your graph the period you chose for your pendulum.

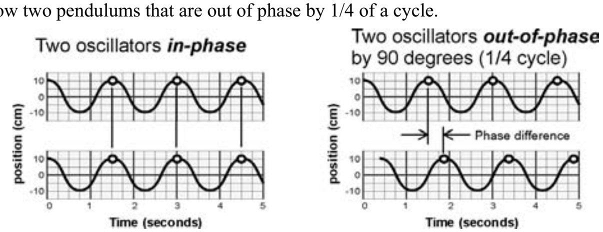
c. How many cycles did your pendulum complete in 30 seconds?

d. If mass does not affect the period, why is it important that the pendulum in a clock be heavy?

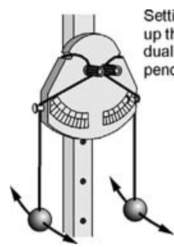
e. Calculate the percent error in your prediction of time from your pendulum clock.

6 Phase

The concept of *phase* is important when comparing one oscillator with another. Suppose you observe two identical pendulums, with exactly the same period. If you start them together, their graphs would look like the picture on the left (below). You would describe the two pendulums as being *in phase* because their cycles are aligned and each one is always at the same place at the same time. If one pendulum is started later than the other, their cycles would be *out of phase.* The graphs on the right (below) show two pendulums that are out of phase by 1/4 of a cycle.



1. Set up a dual pendulum as shown in the diagram. The strings wrap over and around the pegs on either side of the pendulum hanger. The two pendulums swing alongside the pole as shown.
2. Make the string lengths equal for both pendulums. See if you can make them swing in phase, and then out of phase by one-half cycle (180 degrees).
3. Set the pendulums to different lengths. Start them in phase and see what happens to the phase as they keep swinging.
4. Can you construct a pair of pendulums where one has twice the period of the other? Try it.



Setting up the dual pendulum

a. What is the relationship between the lengths of the strings if one pendulum has twice the period of the other?

b. Describe how the phase of the pendulums in step 3 changes over time.

5 6 Example answers

5a. No student response required.

5b. We chose a period of 1.5 seconds.

5c. Our pendulum completed 20 cycles in 30 seconds.

5d. A heavy pendulum in a clock helps make the pendulum swing more steadily and longer.

5e. Our measured time was 29.7 seconds. The difference between the measured and predicted time is 0.3 seconds. 0.3/30 = 0.01 = 1% error.

6a. The pendulum with twice the period has half the string length.

6b. The pendulums begin swinging in phase, then they go out of phase by 90 degrees, then 180 degrees, then they go back to being in phase, and then the pattern begins again.

About the Author

Dr. Thomas C. Hsu is a nationally recognized innovator in science and math education and the founder of CPO Science (formerly Cambridge Physics Outlet). He holds a Ph.D. in Applied Plasma Physics from the Massachusetts Institute of Technology (MIT), and has taught students from elementary, secondary and college levels across the nation. He was nominated for MIT's Goodwin medal for excellence in teaching and has received numerous awards from various state agencies for his work to improve science education. Tom has personally worked with more than 12,000 K-12 teachers and administrators and is well known as a consultant, workshop leader and developer of curriculum and equipment for inquiry-based learning in science and math. With CPO Science, Tom has published textbooks in physical science, integrated science, Earth and space science, and also written fifteen curriculum Investigation guides that accompany CPO Science equipment. Along with the CPO Science team, Tom is always active, developing innovative new tools for teaching and learning science, including an inquiry-based chemistry text.

Foundations of Physics Teacher's Guide

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