11 Merrily We Roll Along!

Purpose

To investigate the relationship between distance and time for a ball rolling down an incline

Required Equipment/Supplies

2-meter ramp
steel ball bearing or marble
wood block
stopwatch
tape
meterstick
protractor
overhead transparencies

Optional Equipment/Supplies

3 photogates with timing system
6 ring stands with clamps

Discussion

Measurement of the motion of a freely falling object is difficult because the speed increases rapidly. In fact, it increases by nearly 10 m/s every second. The distance that the object falls becomes very large, very quickly. Galileo slowed down the motion by using inclined planes. The component of gravity acting along the direction of the inclined plane is less than the full force of gravity that acts straight down—so the change of speed happens more slowly and is easier to measure. The less steep the incline, the smaller the acceleration. The physics of free fall can be understood by first considering the motion of a ball on an inclined plane.

This experiment will require you to make many timing measurements using a stopwatch or, if available, a computer. If you use a stopwatch, develop good timing techniques so as to minimize errors due to reaction time. The computer-photogate system is a powerful stopwatch because it not only eliminates reaction time, but can be used in a variety of timing modes. Since the diameter of the ball can be measured directly, its *speed* can be found by dividing the diameter by the amount

of time it takes to pass through the beam striking the light probe. Strictly speaking, since the ball's speed is increasing as it rolls through the light beam, it exits the beam *slightly* faster than it enters the beam. The width of the ball divided by the time the ball eclipses the light beam gives the *average* speed of the ball through the light beam, not the *instantaneous* speed. But once the ball has picked up speed partway down the incline, its percentage change in speed is small during the short time that it eclipses the light. Then its measured average speed is practically the same as its instantaneous speed.

Procedure

Set up ramp.

Step 1: Set up a ramp with the angle of the incline at about 10° to the horizontal, as shown in Figure A.
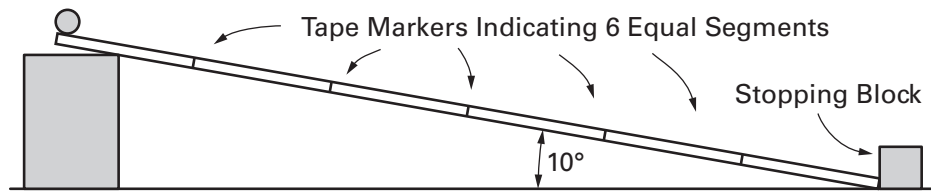

Fig. A

Divide ramp into equal parts.

Step 2: Divide the ramp's length into six equal parts and mark the six positions on the board with pieces of tape. These positions will be your release points. Suppose your ramp is 200 cm long. Divide 200 cm by 6 to get 33.33 cm per section. Mark your release points every 33.33 cm from the bottom. Place a stopping block at the bottom of the ramp to allow you to hear when the ball reaches the bottom.

Distance (cm)	Time (s)			
	Trial 1	Trial 2	Trial 3	Average

Data Table A

Time the ball down the incline.

Step 3: Use either a stopwatch or a photogate to measure the time it takes the ball to roll down the ramp from each of the six points. (If you use the computer, position one photogate at the release point and the other at the bottom of the ramp.) Use a ruler or a pencil to hold the ball at its starting position, and then pull it away quickly parallel to the incline to release the ball uniformly. Do several practice runs with the help of your partners to minimize error. Make at least three timings from each position, and record each time and the average of the three times in Data Table A.

Graph data.

Step 4: Graph your data, plotting distance (vertical axis) vs. average time (horizontal axis) on an overhead transparency. Use the same scales

on the coordinate axes as the other groups in your class so that you can compare results.

Step 5: Repeat Steps 2–4 with the incline set at an angle 5° steeper. Record your data in Data Table B. Graph your data as in Step 4.

Change the tilt of the ramp and repeat.

Distance (cm)	Time (s)			
	Trial 1	Trial 2	Trial 3	Average

Data Table B

1. What is acceleration?

    _____

    _____

2. Does the ball accelerate down the ramp? Cite evidence to defend your answer.

    _____

    _____

3. What happens to the acceleration if the angle of the ramp is increased?

    _____

    _____

    _____

Step 6: Remove the tape marks and place them at 10 cm, 40 cm, 90 cm, and 160 cm from the stopping block, as in Figure B. Set the incline of the ramp to be about 10°.
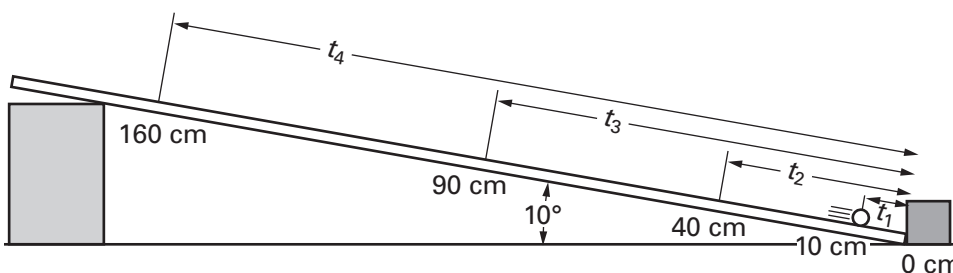
Reposition the tape markers on ramp.

Fig. B

Time the ball down the ramp.

Step 7: Measure the time it takes for the ball to roll down the ramp from each of the four release positions. Make at least three timings from each of the four positions and record each average of the three times in Column 2 of Data Table C.

Column 1	Column 2				Column 3	Column 4
Distance Traveled (cm)	Rolling Time (s)				Time Differences Between Successive Intervals (s)	Time in "Natural Units"
	Trial 1	Trial 2	Trial 3	Average		
10				$t_1 =$		1
40				$t_2 =$	$t_2 - t_1 =$	
90				$t_3 =$	$t_3 - t_2 =$	
160				$t_4 =$	$t_4 - t_3 =$	

Data Table C

Graph data.

Step 8: Graph your data, plotting distance (vertical axis) vs. time (horizontal axis) on an overhead transparency. Use the same coordinate axes as the other groups in your class so that you can compare results.

Study your data.

Step 9: Look at the data in Column 2 a little more closely. Notice that the *difference* between t_2 and t_1 is approximately the same as t_1 itself. The difference between t_3 and t_2 is also nearly the same as t_1. What about the difference between t_4 and t_3? Record these three time intervals in Column 3 of Data Table C.

Step 10: If your values in Column 3 are slightly different from one another, find their average by adding the four values and dividing by 4. Do as Galileo did in his famous experiments with inclined planes and call this average time interval one "natural" unit of time. Note that t_1 is already listed as one "natural" unit in Column 4 of Table C. Do you see that t_2 will equal—more or less—two units in Column 4? Record this, and also t_3 and t_4 in "natural" units, rounded to the nearest integer. Column 4 now contains the rolling times as multiples of the "natural" unit of time.

4. What happens to the *speed* of the ball as it rolls down the ramp? Does it increase, decrease, or remain constant? What evidence can you cite to support your answer?

_____

_____

Step 11: Overlay your transparency graph with other groups in your class and compare them.

5. Do balls of different mass have different accelerations?

_____

_____

Step 12: Investigate more carefully the distances traveled by the rolling ball in Table D. Fill in the blanks of Columns 2 and 3 to see the pattern.

Column 1	Column 2	Column 3
Distance Traveled (cm)	First Four Integers	Squares of First Four Integers
10	1	1
40	2	4
90	3	9
160		

Data Table D

6. What is the relation between the distances traveled and the squares of the first four integers?

_____

_____

Step 13: You are now about to make a very big discovery—so big, in fact, that Galileo is still famous for making it first! Compare the distances with the times in the fourth column of Data Table C. For example, t_2 is two "natural" time units and the distance rolled in time t_2 is 2^2, or 4, times as great as the distance rolled in time t_1.

7. Is the distance the ball rolls proportional to the square of the "natural" unit of time?

_____

_____

The sizes of your experimental errors may help you appreciate Galileo's genius as an experimenter. Remember, there were no stopwatches 400 years ago! He used a "water clock," in which the amount of water that drips through a small opening serves to measure the time. Galileo concluded that the distance d is proportional to the square of the time t.

$$d \sim t^2$$

Step 14: Repeat Steps 6–10 with the incline set at an angle 5° steeper. Record your data in Data Table E.   *Increase tilt of ramp.*

8. What happens to the acceleration of the ball as the angle of the ramp is increased?

_____

_____

Column 1	Column 2				Column 3	Column 4
Distance Traveled (cm)	Rolling Time (s)				Time Differences Between Successive Intervals (s)	Time in "Natural Units"
	Trial 1	Trial 2	Trial 3	Average		
10				$t_1 =$		1
40				$t_2 =$	$t_2 - t_1 =$	
90				$t_3 =$	$t_3 - t_2 =$	
160				$t_4 =$	$t_4 - t_3 =$	

Data Table E

9. Instead of releasing the ball along the ramp, suppose you simply dropped it. It would fall about 5 meters during the first second. How far would it freely fall in 2 seconds? 5 seconds? 10 seconds?

_____

_____

_____

_____

_____

Going Further: Investigating the Speed of the Ball Down the Ramp

Set up computer with photogates.

Ball   Photogates
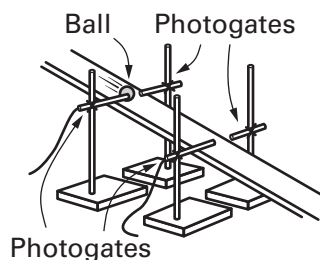
Photogates

You can use the computer to investigate the speed the ball acquires rolling down the ramp. This can be accomplished several different ways using light probes. One way is to position three photogates 10 cm, 40 cm, and 90 cm from the release point on the ramp. The speed of the ball as it passes a photogate can be determined by measuring the time interval between when the front of the ball enters the light beam and the back of the ball leaves it. The distance traveled during this time interval is just the diameter of the ball. Measure the diameter of the ball.

diameter of ball = _____

With the incline set at an angle of about 10°, measure the respective eclipse times for each photogate, and record your timings in Data Table F. To approximate the instantaneous speed of the ball at the three positions, divide the diameter of the ball by the eclipse time. Record the speeds in the table. Also record the average rolling time it took for the ball to travel each distance from the release point, from the information recorded in Data Table C.

Make a plot of instantaneous speed (vertical axis) vs. rolling time (horizontal axis).

Repeat with the ramp at an angle 5° steeper. Use the rolling times recorded in Data Table E.

	Total Distance Traveled (cm)	Eclipse Time (s)	Instantaneous Speed (cm/s)	Average Rolling Time (s)
First Angle	10			
	40			
	90			
Second Angle	10			
	40			
	90			

Data Table F

10. How do the slopes of the lines in your graphs of speed vs. time relate to the acceleration of the ball down the ramp?

_____

_____

_____

11. When you determined the speed of the ball with the photogates, were you really determining instantaneous speed? Explain.

_____

_____

_____

_____

12. As the angle of the ramp increased, the acceleration of the ball increased. Do you think there is an upper limit to the acceleration of the ball down the ramp? What is it?

_____

_____