

# Favorite Experiments in Physics and Physical Science



John D. Mays

 **NOVARE**  
SCIENCE AND MATH  
[novarescienceandmath.com](http://novarescienceandmath.com)

Austin, Texas  
2013

**NOVARE** SCIENCE AND MATH

© 2013 John D. Mays

All rights reserved. No part of this book may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or by information storage and retrieval systems, without the written permission of the publisher, except by a reviewer who may quote brief passages in a review.

Published by  
Novare Science and Math  
P. O. Box 92934  
Austin, Texas 78709-2934

[novarescienceandmath.com](http://novarescienceandmath.com)

Printed in the United States of America

ISBN 978-0-9883228-0-6  
LCCN 2012919155

Other titles by John D. Mays, published by Novare Science and Math:

*Accelerated Studies in Physics and Chemistry*  
*A Mastery-Oriented Introductory Curriculum*

*Introductory Physics*  
*A Mastery-Oriented Curriculum*

*Teaching Science so that Students Learn Science*  
*A Paradigm for Christian Schools*

*The Student Lab Report Handbook*  
*A Guide to Content, Style and Formatting for Effective Science Lab Reports*

*Science for Every Teacher, Volume 1: Physics*

*These may all be obtained at [novarescienceandmath.com](http://novarescienceandmath.com).*

---

# Contents

---

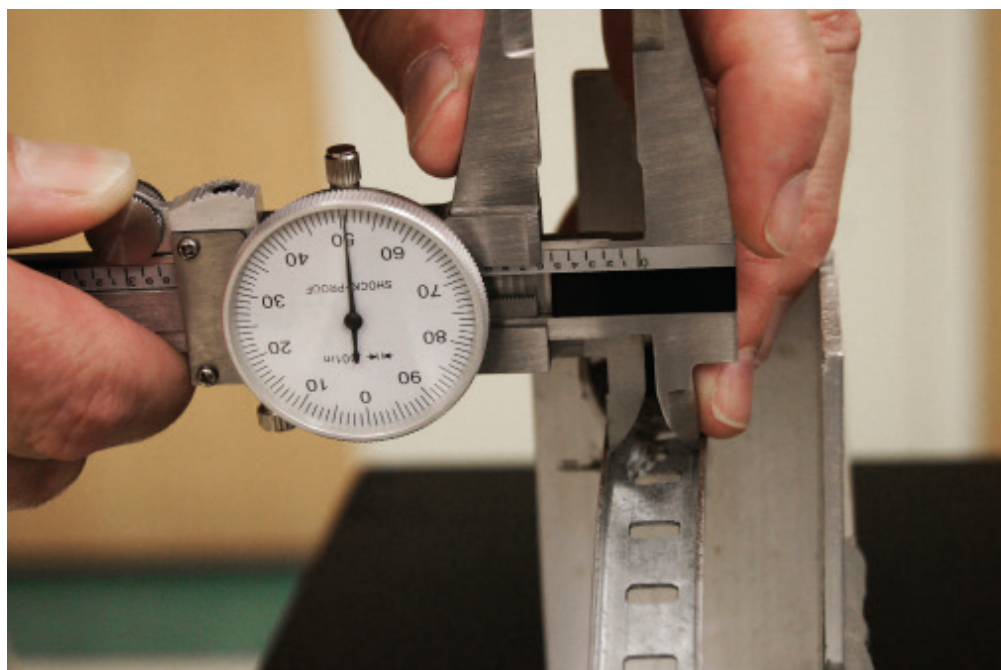
<b>Introduction</b>	<b>1</b>
Audience	1
Why I Wrote This Book	1
How Many Labs to Do	2
The Importance of Real Lab Reports	2
Do We Need This Much Detail?	3
Teacher Background	3
Accuracy, Precision, Significant Digits, Units of Measure, etc.	3
Learning Objectives for a Secondary Science Laboratory Program	4
Student Instructions for Experiments	5
Organization	5
A Note About Experimental Error	6
 <b>Part 1      Experiments for Physical Science</b>	 <b>9</b>
 <b>Experiment 1      The Pendulum Lab</b>	 <b>11</b>
Learning Objectives	11
Materials Required (per lab team, four students max per team)	11
Experimental Purpose	11
Overview	11
Pre-Lab Discussion	12
Scoring the Student Lab Reports	14
Student Instructions	14
 <b>Experiment 2      The Soul of Motion Lab</b>	 <b>21</b>
Learning Objectives	21
Materials Required (for the class)	22
Experimental Purpose	22
Overview	22
Experimental Conditions	24
Pre-Lab Discussion	24
Detailed Experimental Protocols	27
Alternate Experimental Method	29
Student Instructions	30
 <b>Experiment 3      The Hot Wheels Lab</b>	 <b>43</b>
Learning Objectives	43
Materials (for the class)	43
Experimental Purpose	44
Overview	44
Photogate Notes	45

Student Preparation	45
Pre-Lab Discussion	46
Detailed Experimental Protocols	47
Student Instructions	48
<b>Experiment 4      DC Circuits</b>	<b>55</b>
Learning Objectives	55
Materials Required (per group)	55
Experimental Purpose	56
Overview	56
Student Preparation	56
Pre-Lab Discussion	57
Additional Technical Considerations	58
Student Instructions	58
<b>Experiment 5      The Solubility Lab</b>	<b>71</b>
Learning Objectives	71
Materials Required (per student group)	71
Experimental Purpose	72
Overview	72
Pre-Lab Discussion	75
Student Instructions	75
<b>Experiment 6      The Density Lab</b>	<b>83</b>
Learning Objectives	83
Materials Required (per group)	83
Experimental Purpose	84
Overview	84
Pre-Lab Discussion	87
Student Instructions	87
<b>Part 2      Demonstrations for Physical Science</b>	<b>97</b>
Retrograde Motion	99
What is an Ellipse?	99
Newton's Third Law of Motion	101
Charles' Law	103
Gravitational Potential Energy and Kinetic Energy	114
Work	114
Conservation of Momentum	116
Heat Transfer Processes	119
Kinetic Theory of Gases	119
Specific Heat Capacity	120
Reflection	123
Refraction	123
Diffraction and Interference	124
Interference	126

Resonance	127
Frequencies of Sound	129
Loudness of Sound	129
Harmonics and Timbre	130
Setting Up Your Lab for Sound Demonstrations	131
Electrochemistry	135
Static Electricity	136
Magnetic Fields	140
Ampère's Law	140
Faraday's Law of Magnetic Induction	142
Motors	145
Generators	147
Synthesis and Activation Energy: Burning Magnesium	151
Single Replacement and Synthesis: Hydrogen Production 1	152
Double Replacement and Decomposition: Baking Soda and Vinegar	155
Single Replacement and Synthesis: Hydrogen Production 2	156
Single Replacement and Synthesis: Hydrogen Production 3	157
Collision Theory and Activation Energy: Exploding Coffee Creamer	161
<b>Part 3 Experiments for Upper-Level Physics</b>	<b>167</b>
<b>Experiment 1 The Bull's-Eye Lab</b>	<b>169</b>
Learning Objectives	169
Materials Required (per team)	169
Experimental Purpose	170
Overview	170
Pre-Lab Discussion	170
Additional Experimental Details	171
Student Instructions	172
<b>Experiment 2 The Friction Challenge</b>	<b>179</b>
Learning Objectives	179
Materials Required (per team)	179
Experimental Purpose	180
Overview	180
Project Schedule	182
Notes on Metal Materials	183
Pre-Lab Notes	184
References	185
Student Instructions	185
<b>Experiment 3 Rotational Kinetic Energy</b>	<b>191</b>
Learning Objectives	191
Materials Required (for the class)	192
Experimental Purpose	193
Overview	193
Theoretical and Algebraic Details	194

Refining the Value for $g$ for Improved Accuracy	195
Precision Measurements	197
Student Instructions	198
<b>Experiment 4      Calorimetry</b>	<b>205</b>
Learning Objectives	205
Materials Required (for the class)	205
Experimental Purpose	206
Overview	206
Temperature Measurements	207
Aluminum and Copper Details	208
Pre-Lab Discussion	209
Post-Lab Discussion	209
Student Instructions	210
<b>Experiment 5      Sound</b>	<b>215</b>
Learning Objectives	215
Material (for the class)	215
Overview	216
Theoretical Background	217
Analysis	219
Time Averaging and Weighting Curves	220
Pre-Lab Discussion	220
References	222
Student Instructions	222
<b>Part 4      Demonstrations for Upper-Level Physics</b>	<b>229</b>
Projectile Motion: The Monkey and the Hunter	229
Torque: The Magic Belt on Hook	231
Moment of Inertia: Rolling Ring and Disk on Ramp	232
Centripetal Force: Whirling Ball on a String	232
Conservation of Angular Momentum: Spinning Stool and Weights	234
Pressure and Density: Cartesian Diver	234
Pressure and Density: U-Tube Manometer	235
Pressure and Hydraulics: Miniature Floor Jack	236
Pressure and Bernoulli's Equation: Bernoulli Paper	236
Atmospheric Pressure and Sound	237
Pressure and Phase Transitions: Boiling Water at Room Temperature	238
Pressure and Phase Transitions: Pressure-Induced Freezing	238
Thermodynamics: Drinking Bird	240
Thermodynamics: Fire Syringe	240
Thermodynamics: CO <sub>2</sub> Water Bottle	241
RC Circuits: Charging Capacitor	242
Waves and Light: Interference and the Grating Equation	243
Waves and Light: CD Track Pitch and the Grating Equation	245
Light Polarization: Crossed Polaroid Films	247

<b>Appendix</b>	<b>Measurement Basics</b>	<b>249</b>
	A Note About Experimental Error	249
	Types of Error	250
	Accuracy and Precision	251
	Parallax Error and Liquid Meniscus	252
	Significant Digits	253
	Proper Measurement Procedures	257
	Units of Measure	259
<b>Index</b>		<b>262</b>









---

## Part 1

## Experiments for Physical Science

---

It is common these days for middle school students to take a course entitled “Physical Science.” Although some of these experiments could be adapted for use in middle school, the six experiments in this section were developed for *high school* courses of introductory physics and chemistry for ninth grade students. The math involved is generally beyond what middle school students are prepared for.

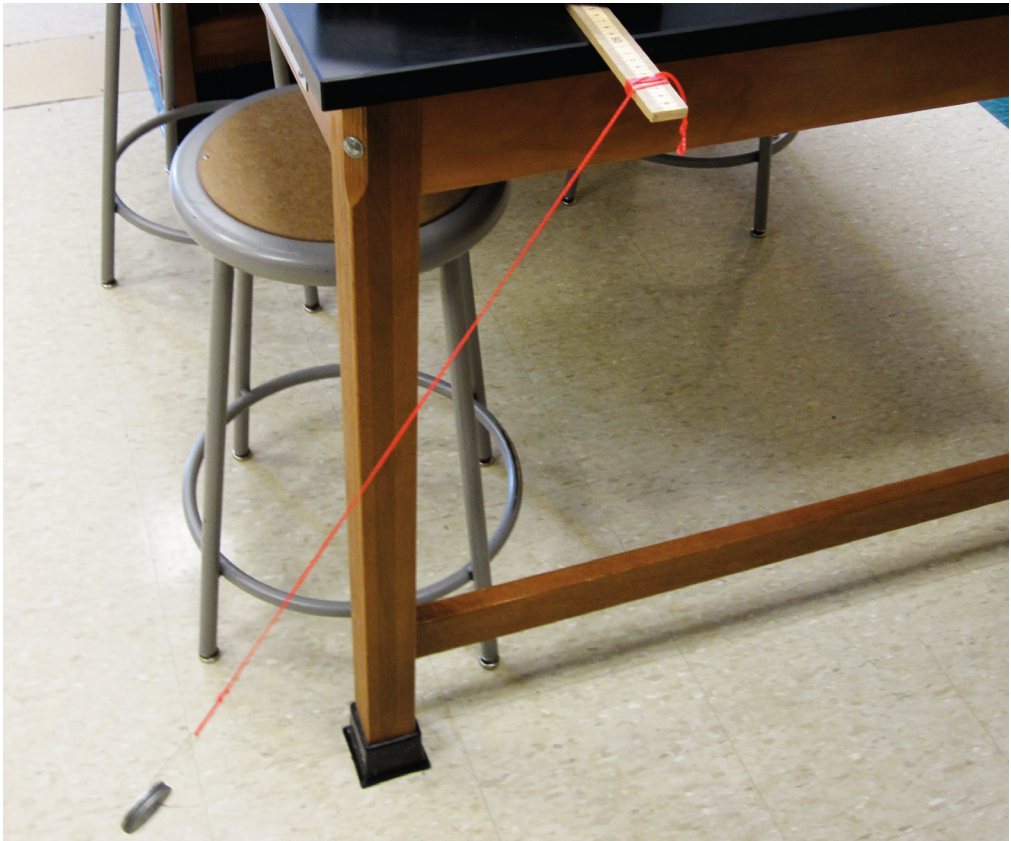
The sequence of experiments is compatible with a standard curriculum in high school physical science, which includes introductory physics and chemistry. These same six experiments are incorporated into my text *Accelerated Studies in Physics and Chemistry*, designed for accelerated or honors-level high school freshmen. Five of these experiments (all but the Solubility Lab) are also incorporated into my text *Introductory Physics*, designed for grade-level high school freshmen.<sup>1</sup>

The real purpose of the first experiment, The Pendulum Lab, is to introduce students to some important experimental methods. The physics of the pendulum is incidental. Since the Pendulum Lab is conceptually simple and there are no graphs to prepare in the report, students can concentrate on learning standard report content and formatting without the complication of preparing graphs. Graphs are added in the second experiment, The Soul of Motion Lab. By holding off graphing until the second report, students can learn the details of report writing in phases during the fall semester, and then polish these skills during subsequent reports. The goal is for students to become proficient at report writing during the freshman year. Then when they encounter more advanced material they can focus their attention on the scientific content of the experiments instead of being distracted by the task of synthesizing the report.

Finally, please see the Introduction (page 6-7) or the Appendix (page 249) for information about my use of the phrase, “prediction-result difference ratio.”

---

<sup>1</sup> Visit [novarescienceandmath.com](http://novarescienceandmath.com) for details on these texts as well as other texts and resources.



---

## Experiment 1

## The Pendulum Lab

---

---

### Learning Objectives

Features in this experiment support the following learning objectives:

1. General objectives for laboratory experiments (see page 4).
  2. Collect data in an organized fashion.
  3. Control variables in an experiment.
  4. Present data in tables.
  5. Develop a complete lab report from scratch.
- 

The real purpose of the fun little Pendulum Lab is to introduce students to experimental methods, including data collection, using a lab journal, manipulating variables one at a time, setting up tables, and report writing. The physics of the pendulum is incidental. For this reason, this is an excellent experiment to perform within the first two weeks of the school year, independent of the topic under study in the curriculum.

Materials for this experiment cost only a few dollars. The experiment is simple to perform and can be conducted in 45 minutes. Students are fascinated by the apparent simplicity of the problem, and the answer to it, which they invariably fail to guess correctly in advance. They are intrigued that such a simple set up can return such a non-intuitive result.

### Materials Required (per lab team, four students max per team)

1. nylon string, 1 meter
2. large paper clip
3. large steel washers (3)
4. meter stick, broom handle, yardstick, or similar item
5. duct tape or masking tape
6. clock with sweep second hand (the classroom wall clock works fine) or stop watch

### Experimental Purpose

Determine the explanatory variables that affect the period of a pendulum.

### Overview

Using simple materials, each student team makes a pendulum and tests it to see how many periods (full swings over and back) the pendulum will complete in a 10-second time

## Favorite Experiments in Physics and Physical Science

interval. Students adjust the variables (the starting angle, the weight, and the length of the string) independently, conducting three separate trials for each configuration. Students record the data in their lab journals.<sup>1</sup> When all trials have been completed, students analyze their data to determine which variables affected the period in their trials. When trials are conducted carefully the data should clearly show that only the length of the string affects the period.

The pendulum is made by unfolding a large paper clip to use as a hook. The paper clip is attached to the end of a string. The other end of the string is tied to the end of a meter stick (or similar item) and the meter stick is placed on a table top so the pendulum hangs over the edge and swings freely. The meter stick is held in place on the table top by masking tape or duct tape. Large washers are hooked onto the paper clip and serve as the weights.

### Pre-Lab Discussion

Cover the following items with the entire class the day before the lab exercise.

1. Define the period of an oscillating system and its unit of measure. In any oscillating system the period is the length of time required for the system to complete one full cycle of the oscillation. Commonly the lower-case Greek letter tau,  $\tau$ , is used to denote the period. The period is measured in seconds (s).
2. Ask students to suggest the possibilities for explanatory variables that could affect the period of a pendulum. In terms of the “scientific method,” this discussion corresponds to the “state the problem” step. There are three mechanical possibilities inherent in the pendulum itself: the weight, the length of the string, and the starting angle from which the pendulum is released. Guide the discussion until these three possible explanatory variables are identified. Confirm that there are other marginal factors that may affect the period such as the air or the rotation of the earth, but that these variables will not be considered in this experiment.
3. Give the teams a few minutes to discuss the three possible explanatory variables as a team. Ask them to consider their own experience and practical mechanical knowledge and form a team hypothesis about which one(s) will affect the period. The teams’ discussions will constitute the “research” step of the scientific method. Instruct the students to document their team’s hypothesis in their lab journals.
4. Explain the fact that since a single period of a pendulum would be too short to measure accurately, we will instead allow the pendulum to swing freely for 10 seconds while the number of complete swings is counted. (One “swing” is all the way over and all the way back to the starting position.) This is much easier to measure and gives us the same information as the period itself. (In fact, we could compute the period from the 10-second swing data by dividing 10 seconds by the number of swings counted.) The team member counting the swings should closely observe the position of the pendulum and estimate the total number of swings in one 10-second interval to the nearest  $\frac{1}{4}$  swing. So the data collected for each trial

---

<sup>1</sup> In addition to data there are many other items that students need to record in their lab journals. For complete details on the use of lab journals, please see *The Student Lab Report Handbook*, available from Novare Science and Math at [novarescienceandmath.com](http://novarescienceandmath.com).

during the experiment consists of the number of complete swings, plus any partial swing rounded to the nearest 1/4 swing, completed by the pendulum in ten seconds.

5. Review the need to test each explanatory variable independently, and present how this can be managed for the three variables being tested here. Since this is probably the first time students have conducted an experiment with three variables to test, the teacher needs to show students how to do this and how to set up appropriate tables for collecting data. These matters can be presented as follows:
  - a. Of the three variables under test, the angle is easiest to change. So it makes sense to set up each configuration of the pendulum and test it at two different starting angles.
  - b. Students will first construct the pendulum with the longest possible string (full length) and the heaviest weight (all three washers). For this configuration the string needs to be 75 to 100 cm long. Students will test this pendulum at each of two different angles. The small angle will be when the pendulum is pulled back about 10 degrees from vertical to be released. The angle can be estimated by one of the team members. Three trials will be conducted at this angle to assure that the data are consistent.
  - c. The large angle will be about 40 degrees from vertical. As before, three trials must be conducted.
  - d. Students must record all the data for these trials in their lab journals in a table like the one below. In each cell in the table students record the number of swings the pendulum completed in the ten second timing interval.

Number of swings completed by long string, heavy weight pendulum		
trial	small starting angle	large starting angle
1		
2		
3		

- e. Since changing the weight on the pendulum can be done quickly, it makes sense to change this variable next. So after completing the six long string, heavy weight trials, students will take off two of the washers, keep every thing else the same, make another table for “long string, light weight” data and conduct the trials, using small and large angles (three trials each) as before.
  - f. After completing the two tables of long string trials, students will shorten the string down to about 25 cm long. Then they conduct trials to fill up two more tables (one for heavy weight, one for light weight) as before. Students will have four tables of data in all, and must conduct 24 separate trials.
6. To assure the best accuracy, encourage students to check that the meter stick is steady while the pendulum is swinging. Tell them also to make sure that the large angle is 3-4 times as large as the small angle, without going over 45 degrees or so from vertical, and that the long string is 3-4 times as long as the short string. The general rule is that for each of the three variables under test, the large value of the

variable should be at least three times the small value. This degree of variation will assure that if the variable does affect the period the data will clearly show it.

7. Teams should divide up the tasks for conducting the trials. One team member watches the clock and gives the signals to start and stop the trials. Another team member pulls back and releases the pendulum at the correct angle on the signal, making sure to start the pendulum from a reliably consistent position. A third team member carefully counts the swings until the stop signal is given, calling the number of swings to the nearest quarter swing. A fourth team member can record the data in his or her lab journal and share it with the other team members after the data collection is complete.

### Scoring the Student Lab Reports

At the school where I developed this experiment we introduce students to the full requirements of report writing in ninth grade. During the rest of the fall term and on into the spring term students are expected to improve the quality of their reports with each new attempt. Our goal is that by the time they finish their freshman year the students are very familiar with standard report content, style and formatting, and have developed solid descriptive and analytical skills. Thus prepared, they enter their tenth grade science courses equipped to engage their science studies at an even deeper level, being able to focus more on the science and less on learning how to write lab reports.

This being the case, this is the students' first report, the first in a series of reports designed to train them in the art of writing good technical papers. The goal for the first one is that they are able to get the major building blocks in place. There is a lot to learn, and writing good reports entails many details, including a lot of specific formatting requirements. My policy for this first report is that any student who reads through the basic chapters of *The Student Lab Report Handbook*<sup>2</sup> and makes a good faith effort to put together a good report that includes the essential ingredients with serviceable English writing will receive at least a B. I expect on this first report that the students will miss many of the formatting requirements described in *The Handbook*. This is not a problem. Writing good reports takes practice, so I gradually raise the grading standard with each new report throughout the year.<sup>3</sup>

### Student Instructions

A set of instructions you may reproduce and give to students begins after the illustrations. This set of instructions is taken from my freshman science texts *Introductory Physics* and *Accelerated Studies in Physics and Chemistry*.<sup>4</sup>

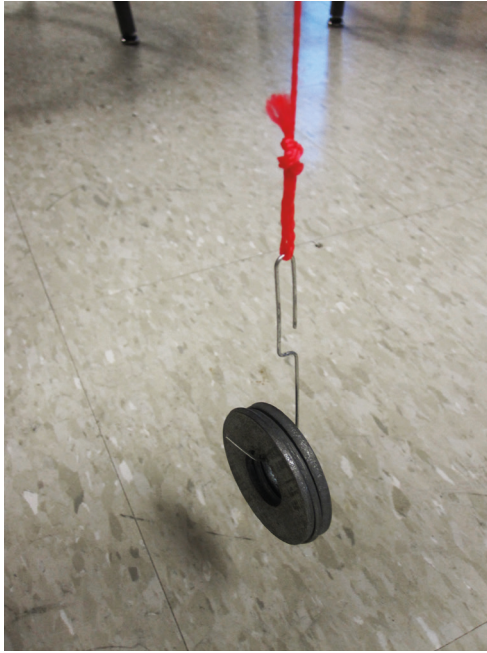
---

2 See the Introduction for details.

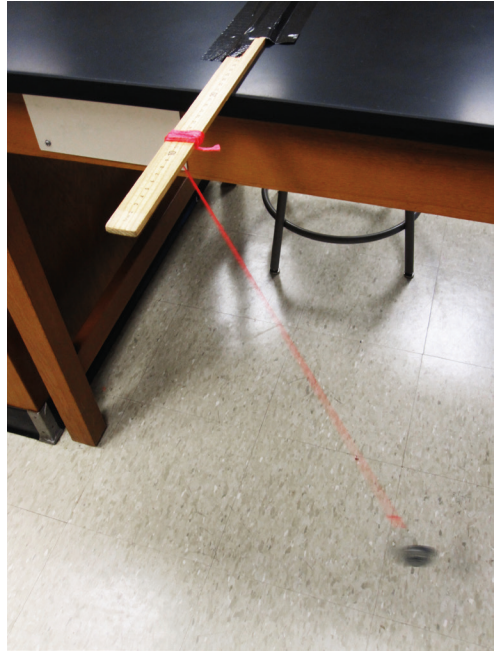
3 I presented a grading rubric for high school lab reports in my 2010 book, *Teaching Science so that Students Learn Science*.

4 Available at [novarescienceandmath.com](http://novarescienceandmath.com).





String, hook and weights ready to go.



The pendulum in action.



### Student Instructions

#### The Pendulum Lab

##### Variables and Experimental Methods

We are going to conduct an investigation involving a simple pendulum. This experiment is an opportunity for you to learn about conducting an effective experiment. In this investigation you will learn about controlling variables, collecting careful data, and organizing data in tables in your lab journal.

To make your pendulum, your team will bend a large paper clip into a hook. Then you can connect the hook to a string, and connect the string to the end of a meter stick. Then lay the meter stick on a table with the pendulum hanging over the edge and tape the meter stick down. Now you can hang one or more large metal washers on the hook for the weight.

In this fun experiment your goal is to identify the explanatory variables that influence the period of a simple pendulum. A pendulum is an example of a mechanical system that is *oscillating*, that is, repeatedly “going back and forth” in some regular fashion. In the study of any oscillating system an important parameter is the *period* of the oscillation. The period is the length of time (in seconds) required for the system to complete one full cycle of its oscillation. In this experiment the period of the pendulum is the response variable you will be monitoring. (Actually, for convenience you will be monitoring a slightly different variable, closely related to the period.) After thinking about the possibilities and forming your team hypothesis, you will construct your own simple pendulum from string and some weights and conduct tests on it to determine which variables actually do affect its period and which ones do not.

In class you will explore the possibilities for variables that may affect the pendulum’s period. Within the pendulum system itself there are three candidates, and your instructor will lead the discussion until the class has identified them. (We will ignore factors such as air friction and the earth’s rotation in this experiment. Just stick to the obvious variables that clearly apply to the problem at hand.)

Then as a team you will continue the work by discussing the problem for a few minutes with your teammates. In this team discussion you will form your own team hypothesis stating which variables you think will affect the period. To form this hypothesis you will not actually do any new research or tests. Just use what you know from your own experience to make your best guess.

The central challenge for this experiment will be to devise an experimental method that tests only one explanatory variable at a time. Your instructor will help you work this out, but the basic idea is to set up the pendulum so that two variables are held constant while you test the system with large and small values of the third variable to see if this change affects the period. You will have to test all combinations of holding two variables constant while manipulating the third one. All experimental results must be entered in tables in your lab journal. Recording the data for the different trials will require several separate tables. For each experimental setup you should time the pendulum three times and record the result in your lab journal. Repeating the trials this way will enable you to verify that you have good, consistent data. To make sure you can tell definitively that

a given variable is affecting the period, you should *make the large value of the variable at least three times the small value in your trials*.

Here is bit of advice about how to measure the period of your pendulum. The period of your pendulum is likely to be quite short, only one or two seconds, so measuring it directly with accuracy would be difficult. Here is an easy solution: Assign one team member to hold the pendulum and release it on a signal. Assign another team member to count the number of swings the pendulum has completed, and another member as a timer to watch the second hand on a clock. When the timer announces “GO” the person holding the pendulum releases it, and the swing counter starts counting. After exactly 10.0 seconds the timer announces “STOP” and the swing counter states the number of swings that have been completed. Record this value in a table in your lab journal. If you have four team members, the fourth person can be responsible for recording the data during the experiment. After the experiment the data writer can read off the data to the other team members so they can enter the data in their journals.

This method of counting the number of swings in 10 seconds does not give a direct measurement of the period, but you can see that your swing count will work just as well for solving the problem posed by this experiment, and is a lot easier to measure than the period itself.

One more thing on measuring your swing count: Your swing counter should state the number of swings completed to the nearest  $\frac{1}{4}$  swing. When the pendulum is straight down, it has either completed  $\frac{1}{4}$  swing or  $\frac{3}{4}$  swing. When it stops to reverse course on the side opposite from where it was released, it has completed  $\frac{1}{2}$  swing.

When you have finished taking data, review the data together as a team. If you did the experiment carefully your data should clearly indicate which potential explanatory variables affected the period of the pendulum and which ones did not. If your swing counts for different trials of the same setup are not consistent, then something was wrong with your method. Your team should repeat the experiment with greater care so that your swing counts for each different experimental setup are consistent.

Discuss your results with your team members and reach a consensus about the meaning of your data. You should expect to spend at least four hours writing, editing and formatting your report. Lab reports will count a significant percentage of your science course grades throughout high school, so you should invest the time now to learn how to prepare a quality report.

Your goal for this report is to begin learning how to write lab reports that meet all of the requirements outlined in *The Student Lab Report Handbook*. One of our major goals for this year is to learn what these requirements are and become proficient at generating solid reports. Nearly all scientific reports involve reporting data, and a key part of this first report is your data tables, which should all be properly labeled and titled.

After completing the experiment all of the information you will need to write the report should be in your lab journal. If you properly journaled the lab exercise you will have all of the data, your hypothesis, the materials list, your team members’ names, the procedural details, and everything else you need to write the report. Your report must be typed, and will probably be around two or three pages long. You should format the report as shown in the examples in *The Student Lab Report Handbook*, including major section headings and section content.

Here are a few guidelines to help you get started with your report:

1. There is only a small bit of theory to cover in the Background section, namely, to describe what a pendulum and its period are. You should also explain why we are using the number of swings completed in 10 seconds in our work in place of the actual period. As stated in *The Student Lab Report Handbook*, the Background section must include a brief overview of your experimental method and your team's hypothesis.
2. Begin your Discussion section by describing your data and considering how they relate to your hypothesis. In this experiment we are not making quantitative predictions, so there will be no calculations to perform for the discussion. We are simply seeking to discover which variables affect the period of a pendulum, and which do not. Your goal in the Discussion section is to identify what your data say and relate that to your reader.
  - a. What variables did you manipulate to determine whether they had any effect on the period of the pendulum?
  - b. What did you find? Which ones did affect the period? How do the data show this?
  - c. Were you surprised by what you found?
3. If you would like to produce a really outstanding report, consider exploring the following questions in your discussion:
  - a. Many clocks use pendulums to regulate their speed. What is it about pendulums that makes them good for this?
  - b. How would this work in an actual clock?



Favorite Experiments in Physics and Physical Science





---

### Learning Objectives

Features in this experiment support the following learning objectives:

1. General objectives for laboratory experiments (see page 4).
  2. Present theoretical predictions and experimental results on the same set of axes in a graph.
  3. Use theory to make quantitative predictions of experimental results.
  4. Use proper formatting and presentation for graphs in reports.
  5. Explore and learn how to use unfamiliar scientific equipment.
- 

**F**or over a decade my freshman students called this investigation of Newton's Second Law of Motion the Pick-up Truck Lab. For many of them, especially the boys who love exhibiting their strength while pushing my Ford F-150 pick-up truck around in the school parking lot, it is probably the most enjoyable experiment in the entire year. For getting the students out of the classroom and allowing them to be physically active, this is about as good as it gets in a physics class!

I got the idea for this experiment from a journal article I read by another physics teacher over 20 years ago.<sup>1</sup> In this experiment students have their first chance to use theory to predict the outcome of an experiment and compare their experimental results to their predictions. If done well the difference between the predictions and the results can turn out surprisingly low, significantly less than 5%. The subsequent report entails learning how to prepare graphs showing both predicted and experimental values.

As I write this I have just replaced my old truck with a new KIA Soul and have modified the apparatus to make it work with this new vehicle. I am including photos of both vehicles to suggest different ways to make the experiment work. I have also done the experiment with a Dodge 4-door sedan (Intrepid). I suppose many different vehicles could be made to work. The main requirements are that the rear of the vehicle is vertical or nearly so for proper placement of the force-reading scales, and that the vehicle is not too large, so that reasonable amounts of force result in reasonable amounts of acceleration. If you (the teacher) do not own a suitable vehicle for this experiment try getting one of the parents involved with his or her own vehicle. They will have a great time with the students.

Achieving results within 5% of the predictions was only possible because while doing this experiment over and over I chased lurking variables like a bloodhound for over a dozen years. I learned a great many details that can make this experiment a resounding success. Naturally, I am going to present all these here in this chapter, but the downside of doing so is that the chapter will be somewhat long. Believe me, this experiment is so much fun that it is all worth it.

---

<sup>1</sup> Unfortunately, I have been unable to locate this article in order to cite it appropriately.

## Favorite Experiments in Physics and Physical Science

Even though the lengthy instructions may make this experiment appear daunting, in its basic form it is actually easy to do and requires no special equipment. Students simply push a car using inexpensive bathroom scales to measure and monitor the force, while other students time the vehicle in order to establish an experimental value for the acceleration. The forces the pushers apply are used to work up theoretical values for the acceleration. I suggest that when you perform this experiment for the first time you go with this simple approach. Then whenever the budget permits, you can look into acquiring the equipment and building the apparatus for the more sophisticated approach.

Setup and data collection for this experiment can be completed in approximately 50 minutes.

### Materials Required (for the class)

Note: If bathroom scales are used for the experiment, you will need two of them. If the PASCO equipment is used for the experiment and is fastened to a support rack as described below, then you will still need one bathroom scale for weighing the driver and the support rack.

1. bathroom scales (2); (Stay away from digital scales. Humans cannot respond as fast to changing numerals as they can to a swinging pointer. Use inexpensive, old-fashioned scales that read with a dial or needle.)
2. pick-up truck, KIA Soul, or other vehicle for the purpose
3. measuring tape, such as the 30 meter, wind-up metric tape AP6323 available from Flinn Scientific ([flinnsci.com](http://flinnsci.com))
4. stop watch
5. duct tape

Additional optional equipment if digital readers are used:

6. PASPORT 2-Axis Force Platform, PS-2142 (2); (available from PASCO, [pasco.com](http://pasco.com))
7. Xplorer GLX (2); (available from PASCO, [pasco.com](http://pasco.com))
8. Force platform handle set, PS-2548 (2); (available from PASCO, [pasco.com](http://pasco.com))
9. Force platform support rack (see the illustrations below for construction suggestions)

### Experimental Purpose

Use Newton's Second Law of Motion to predict the acceleration of the vehicle under different applied forces and compare the predicted accelerations to experimental values.

### Overview

The entire class conducts this experiment as a group, sharing the data recorded. The idea is to push a vehicle with known, constant forces over a known distance (10.00 m) starting from rest while timing it with a stop watch. The resulting acceleration may be computed as



$$a = \frac{2d}{t^2}$$

Two students push the vehicle simultaneously, pressing on the rear of the vehicle with bathroom scales or other devices so they can monitor the forces they are applying. Four different values of force are applied, resulting in four different values of acceleration. Three trials are conducted for each force. A set of trials is judged valid if the three time measurements are within a one-second range from highest to lowest. For a given force value, the times from all three trials are averaged to determine the experimental value of acceleration.

The predicted values of acceleration for the four different applied forces are determined from Newton's Second Law,

$$a = \frac{F}{m}$$

Before the day of the experiment the teacher must drive the experimental vehicle to a weighing station to be weighed (full tank of gas, no driver). I use a local landscaping supply company that has a truck scale for weighing trucks hauling stone, and when I tell them I am a science teacher they are always happy to weigh my car. You can report the weight in pounds to the students and let them determine the vehicle mass for themselves. Values of acceleration are computed from the total applied forces and the vehicle mass. (The mass must include the mass of the experimental driver and the force measurement equipment, as described below.)

The acceleration predictions are much more accurate if friction forces are deducted from the values of force applied by the students. A good approximation for the total friction force is found by having one student push the car as slowly as possible while barely keeping it in motion at a constant speed. (This must be done in the location where the experiment is to be performed, because the slope of the pavement makes a huge difference in how much force is required to overcome the kinetic friction of the brake pads and wheel bearings.) The value of the force required to do this is deducted from each applied force to obtain the net force values used in Newton's Second Law for the predictions.

As recommended in the original article on this idea, I conducted this experiment for many years using two inexpensive bathroom scales purchased from a discount store for under \$10 each. The students simply hold the scales against the back of the car or truck and watch the dial on the scale, adjusting the strength of their pushing to hold the force as steadily as possible on the desired value. The scales remain in place by friction while the forces are applied. The results are surprisingly good, especially considering that the forces are impossible for the pushers to hold steady. The forces bounce up and down above and below the desired value. But with two people pushing they average out well to give an average value close to the desired value.

Over the years as funds became available I looked into higher-tech ways of monitoring the forces. PASCO makes a nice tool for measuring the forces, the PASPORT 2-Axis Force Platform, that connects to a portable data collection tool called the Xplorer GLX. (Both of these are expensive, and you need two sets for this experiment. But the Xplorer GLX is a versatile tool that can be used for many other types of data collection, including several other experiments and demonstrations described in this book.) The force platforms are too bulky and heavy for the pushers to use them without support, so I built a wooden rack to mount on the back of the pick-up truck to hold the two force platforms. Now that I am doing the

## Favorite Experiments in Physics and Physical Science

experiment with a KIA Soul, I modified the rack so it would work with this different vehicle. Both versions of the support rack are shown in the illustrations beginning on page 31.

The PASCO equipment allows one to collect data into a digital file and display the data graphically in a computer application for analysis. The display on the Xplorer GLX can also be set to show a simulation of an analog dial, which is much easier for the pushers to read and respond to than a digital display. One can also calibrate the maximum reading of the display of the Xplorer GLX for maximum resolution. I now conduct this experiment every year using the PASCO equipment. The students get a kick out of the digital equipment, and the whole set up is less finicky than doing the experiment with bathroom scales (which are hard to zero or tare, and tend to slip around). In summary, go high-tech if you can. But if you can't, this lab is still a ton of fun. The students love it and the data collection and analysis are very effective ways of learning about Newton's Second Law of Motion.

### Experimental Conditions

The optimum conditions for doing this experiment would be inside a large, air-conditioned building, on a clean, smooth, level surface. If you have access to such ideal conditions take advantage of them. Here's why such conditions matter.

First, wind can make a significant difference in the acceleration of the vehicle. This problem is significantly worse when using a hatch-back vehicle with the hatch open, as with my KIA Soul. The open hatch catches the wind, affecting the net force on the car and causing large errors. So select a location for the experiment where the wind is blocked by a nearby building.

Second, in a parking lot all surfaces are intentionally designed to slope for proper drainage. This means that the best you can do is minimize the slope of the pavement, but you can't eliminate it. Select a location with as little slope as possible.

Third, the slope of the pavement may not be uniform, and different amounts of slope will produce different net forces on the car. Even over the 10-meter course of the car timing zone the slope can change enough to cause significant error. Select a location where the slope of the pavement is as uniform as possible.

The air conditioning is not really necessary. But in Texas, doing this experiment in September, the students pushing the car tend to get hot and sweaty (and stinky). Naturally, we gung-ho scientists never let little things like this get in our way, but I always wondered if I should try to persuade the Athletic Director to let us perform this experiment in the gym! If you have an outdoor basketball court on level concrete, that would be close to ideal. If the court is sheltered from wind then it would have everything you need except cool weather.

If you have to make do out in a parking lot somewhere, you must at least choose a location horizontal enough that the vehicle will not begin to roll by itself anywhere in the timing zone after given a little push.

### Pre-Lab Discussion

Students should read the Student Instructions handout for basic information about the purpose of the experiment and procedures. Additionally, review the following items with students the day before the experiment:

1. One of the major ways theories are tested is by forming testable hypotheses and devising tests to try to confirm them. In this experiment that is what we are doing. Our theoretical framework is Newton's Laws of Motion. Our hypothesis is that we can accurately predict the acceleration of the vehicle using the Second Law. Our experimental plan is to predict the acceleration of a vehicle as a function of force applied at the back, measure the actual acceleration for the same forces, and compare the results to the predictions by computing the prediction-result difference ratio.<sup>2</sup>
2. Newton's Second Law may be written as

$$a = \frac{F}{m}$$

Written this way the equation indicates that the acceleration is the dependent variable and depends on the force, the independent variable. This is the equation we will use to make our predictions. All we need to know to predict the acceleration for a given force is the mass of the car. The teacher is going to provide the class with the weight of the car which students can use to determine the mass of the car. We also need to include the masses of the driver and of the force measurement equipment, if significant (see below).

Newton's Second Law is a linear equation. Acceleration varies in direct proportion to force, with constant of proportionality equal to  $1/m$ . A graph of this equation should be a straight line with slope  $1/m$ .

3. There is a lot of friction in the brake pads of a car, because the pads touch the disk rotors all the time, not just when the brakes are applied. This means that not all of the force applied by the pushers is going to contribute to the acceleration. Some of it is simply overcoming the friction of the brake pads (and wheel bearings). Thus, we are going to strive for maximum accuracy by measuring the friction force at the beginning of the experiment. Then we will subtract it from the forces applied by the pushers and use this net value of force in our calculations of the predicted values. Thus our equation for the predicted values will be

$$a = \frac{1}{m} \cdot (\text{Force applied by pushers} - \text{estimated friction force})$$

(Many students, unknowledgeable about cars, will spell brakes as "breaks." This friction discussion is a good time to have them make note of the correct spelling.)

4. To determine our experimental values of acceleration we will use the equation

$$a = \frac{2d}{t^2}$$

---

2 See Appendix.

## Favorite Experiments in Physics and Physical Science

We will make a timing zone on the ground with start and finish lines indicated by duct tape. The timing zone will be 10.00 meters long and we will time the vehicle during each trial with a stop watch. (Alas, many students, ignorant of the world of hardware, think duct tape is spelled “duck” tape, so you may as well inform them now of the correct spelling of this word, too. The fact that there is a brand of duct tape called Duck Tape just confuses the matter.)

5. Discuss the four different force values to be used during the experiment. Quote the force values in pounds if you are using bathroom scales, and show the students how to convert the values into newtons for their analysis. If you are using the PASCO force sensors you can work directly with forces in newtons. Values I have used in the past are as follows:

F-150 Pick-up truck:

110 N each (220 N total), 130 N each, 170 N each, and 200 N each.

KIA Soul:

100 N each (200 N total), 125 N each, 150 N each, and 175 N each

Note: The values above are based on the weights of the vehicles (the Soul weighs a lot less than the F-150) and the friction forces that had been measured previously for the specific vehicle involved, which were 110 N for the pick-up truck and 140 N for the Soul. The first time you conduct this lab you will want to measure the friction before making final decisions about the specific forces to use. However, experience has shown that forces above 200 N each, which is over 40 pounds, are not reasonable, since students cannot reliably push harder than this on an accelerating vehicle and keep the force up for the duration of the 10-meter trials.

6. We will conduct at least three separate trials for each force value. We will judge our data to be valid when we get three time measurements that are within one second of each other. That is, the spread between the highest and lowest times is 1.00 s or less, with a third time in between. This will require our pushers to really focus on applying constant forces. It is impossible to make them perfectly constant, but constancy is the goal.
7. One of the main elements in the report for this experiment will be a graph of acceleration vs. force showing the four predicted acceleration values and the four experimental acceleration values on the same graph. After the experiment we will go over in detail how to construct such a graph using Microsoft Excel.<sup>3</sup> We expect the four predicted values to make a perfect line. The experimental values of acceleration will correspond to the same values of force as the net force values used for the predictions, so we should see the experimental values lying close to the predicted values, either directly above or directly below. If our data are accurate, the experimental values should follow a nice, linear trend.

---

<sup>3</sup> This procedure is described step-by-step, with color screen captures for reference, in *The Student Lab Report Handbook*. See the Introduction for details.

8. We need to select a student to be the driver. The vehicle will not be running during the experiment, but someone has to hold the steering wheel steady. In electing this student we will give precedence to anyone who has a driver's permit already. There is one caveat: The driver must consent to being weighed and having his or her weight published to the class.
9. In addition to the driver, we need a timer to operate the stop watch, and a data recorder to log the data reported by the timer into his or her lab journal. We will use two students as pushers for a given force, and they will push the vehicle as many times as they have to until we get three valid time measurements. Then we will get two fresh pushers for the next force value. Students not involved in any of these tasks will be needed on the return pusher crew to return the vehicle to the starting line for the next trial.
10. For a large vehicle like a pick-up truck, the work of pushing is quite physically demanding. Without adequate strength the force a student applies will inevitably decrease as the vehicle picks up speed. This means that with young students like freshmen, most girls and the smaller boys can't really handle it (despite their burning enthusiasm for experimental science!). Thus, the larger boys will be needed for the pushing. (That's just the way it is. Life isn't fair.) With a smaller vehicle like the Soul, lower forces can be used because the vehicle mass is significantly lower. This allows a more democratic selection process for the coveted position of pusher!
11. Students who will be assigned as pushers need to wear appropriate shoes. They will need to lean over and push hard without their shoes slipping on the pavement. Sport shoes are best. Cowboy boots or other smooth-soled shoes are worst.

## Detailed Experimental Protocols

1. Select the location for the experiment based on considerations discussed in Experimental Conditions above.
2. Using duct tape, the students mark off two parallel lines 10.00 meters apart for the timing zone. Position the student timer with the stop watch at the finish line. The stop watch should be started on the audible signal, and stopped when the front bumper of the vehicle crosses the finish line.
3. Make the following measurements and record the data. (It is best to do this before beginning the trials with the vehicle, otherwise one tends to forget about them.)
  - a. Weigh the driver, reporting the weight to the data recorder.
  - b. Weigh the force platforms and mounting bracket, and report the weight. (If bathroom scales are being used the weight is insignificant and this step can be neglected.)
  - c. Determine the friction in the brakes by having one student push the vehicle as slowly as possible, but at a steady, constant speed. Estimate the average force the student has to apply to accomplish this. Record this force value, to be used later as the friction force. Note: All modern brake pads have metal particles in them that oxidize (rust) from the moisture in the air whenever the vehicle is at rest. This rust is rubbed off when the brake pads are in use. To make sure

## Favorite Experiments in Physics and Physical Science

the friction force is consistent during the experiment, drive the car around the parking lot a couple of times while holding the brake on slightly with your left foot. This will polish the rust off the brake pads and make the friction both low and constant during the experiment.

4. Place the vehicle transmission in neutral and leave it there for the duration of the experiment.
5. Tare the force scales. Dial-type bathroom scales have zeroing knob. The PASCO force platforms have a button for setting the zero. Mounted vertically, the readers never read quite zero, but they are close (within 10 or 15 N of zero, which is only 1/4 lb or so).
6. For each new trial the vehicle is positioned with its front bumper at the starting line. The vehicle is at rest with the student driver in the driver's seat holding the brake on.
7. The two pushers apply the appropriate force to their scales or force platforms and hold it there. They need to pre-load this force before the starting signal and hold it steady in a ready position.
8. If you are using the PASCO force platforms with the Xplorer GLX data collectors, you will also need to assign two students to hold the data collectors, which serve as the force indicators, in front of the pushers' faces, walking along with them so the pushers can monitor the forces they are applying. Of course, if you are using bathroom scales this is not necessary.
9. Tell the pushers to keep their hands and fingers completely on the scales. No fingers should hang off the edges and push on the vehicle directly. (This is more of a problem with the bathroom scales because the pushers have to hold them up, tempting them to wrap their fingers around the sides.)
10. To start the trial someone with a loud, projecting voice does the count-off: READY—SET—GO! (I always reserve this esteemed position for myself, the leader of the class, and the guy with the loudest and most projecting voice around.) On "GO," the timer starts the stop watch and the driver releases the brake. Be sure to emphasize to the pushers that at the GO signal they are to do ABSOLUTELY NOTHING. They are already at the ready, holding the correct value of force on the scale, and they just need to hold it there. Analysis of data files collected with the Xplorer GLX shows that the pushers tend to feel the joy of the moment and push harder when the GO signal is given. May heaven bless them for their enthusiasm, but this obviously introduces error. So tell them to hold rock steady on the force value, and not to give any joyful nudges when the GO signal occurs.
11. Another important thing to warn the pushers about is that as the vehicle picks up speed it becomes increasingly difficult to maintain the force value. Analysis of Xplorer GLX data files also shows that forces tend to decrease toward the end of the run. This is because it is hard for the pushers to maintain the force while keeping up with the vehicle and maintaining traction on the ground. Warn the pushers about this, and admonish them constantly during each run to "Hold it steady, pushers! Don't fade out!" This problem is all the more significant at the high force values, so encourage those pushers accordingly.

12. When the front bumper of the vehicle crosses the finish line, which the timer is watching carefully from her or his assigned position, the timer stops the stop watch and reports the time value to the data recorder who is standing by. The leader should keep track of the data and continue authorizing new trials until the one-second spread criterion for three trials is achieved.
13. After crossing the finish line the driver can gently apply the brake to help stop the vehicle. It is a good idea to warn the driver not to hit the brake too suddenly or the pushers might get unpleasantly bumped around.
14. After the vehicle is brought to a stop the other students leap into action and push the vehicle back to the starting position, carefully lining up the front bumper with the starting line in preparation for another trial. You may as well warn them right from the first to take it easy when pushing the car back into position. They tend to get enthusiastic, and I am always concerned that if the vehicle gets moving too fast it will run over someone's foot. So tell them to push it back at a nice calm, reasonable speed, and to stay on duty until the car is lined up at the starting line and the driver has the brake on, ready for the next trial.
15. After the experiment is complete and your class is back in the classroom, have the data recorder share the official time data with the other students so everyone can get the data into their lab journals.

### Alternate Experimental Method

If you have the funds to procure the PASCO equipment then you might be interested in an experimental method that can improve the accuracy of this experiment even further. The downside to this method is that you will have to spend a lot of time fooling with the data files during and after the experiment.

The major source of error in this experiment is the difference between the force value target and the actual forces applied to the vehicle by the pushers. My procedures try to minimize this source of error by calling for a maximum spread of one second in the time data for the trials at a given force. However, this does not eliminate the error. It is quite possible that the pushers undershoot or overshoot their targets very consistently. This would make the times consistent, but there would be an undetected bias in the data. This alternate method takes care of this problem.

The alternate method works like this. Select 10 or 12 force values ranging from forces that will barely make the car accelerate (about 100 N each) up to the maximum the students can deliver (around 200 N each). Then assign all students other than the driver and the timer to pushing duty (smaller kids to lower force values, big beefy athletes to higher values). Then perform a single trial at each chosen force and use the Xplorer GLX not only as a reader but also as a data recorder. With actual force data for the trial you can use the mean value of the force data to construct your predictions.

As an example, with the primary method you might have a target force for a set of trials at 150 N. Your pushers would do the best they can, and you would use 150 N (times two for two pushers) in your prediction of the acceleration for that force. Using the alternate method you just tell the pushers to push at 150 N but you record the force data file while it is happening. The actual values of the forces the pushers produce do not matter, because you



## Favorite Experiments in Physics and Physical Science

will take the mean values from the two data files for the two pushers and use these actual mean values to calculate your acceleration prediction.

This method requires that during each trial the students holding the Xplorer GLX data readers for the pushers to see must also be responsible for starting and stopping the data recording during the trial. They should accurately start the recording on the GO signal, and stop the recording on a STOP signal called out by the stop watch operator.

Since accuracy of maintaining a specific force is not an issue with this method, there will be much more flexibility in assigning students to push the vehicle. When accurate force maintenance is required, strong students capable of holding the force values all the way through the trial must do all the pushing. By using the mean force from the data file all students can be involved in the pushing without fear that those with modest strength will fade at the end of the trial.

### Student Instructions

A set of instructions you may reproduce and give to students begins after the following illustrations. This set of instructions is taken from my freshman science texts *Introductory Physics* and *Accelerated Studies in Physics and Chemistry*.<sup>4</sup>

---

<sup>4</sup> Visit [novaescienceandmath.com](http://novaescienceandmath.com) for details.



Force platform mounting bracket as originally built for a pick-up truck consists of a 1x6 across the top fastened with screws to a panel of 3/4-inch plywood with a piece of aluminum angle. The wooden lip across the bottom supported the weight of the force platforms.



Close-up of the bracket. Visible on the edge of the plywood is an eyescrew used for a cable that held the force platforms in place. Also visible is one of the two sections of dowel rod that fit into the stake holes of the pick-up bed. (Alas, new trucks don't have stake holes! How will future generations of physics teachers cope?)



Two boys pushing the force platform on the back of the truck while two girls carry the Xplorer GLX readers, holding them where the boys can see them while they push.