Physics 2130

Physics for Science and Engineering Majors I

Laboratory Experiments

Department of Physics and Astronomy
The University of Toledo
Toledo, Ohio

Credits and Acknowledgements

Real Time Physics: Active Learning Laboratory

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Note: These materials have been modified locally by R.G. Bohn.

Physics 2070 Labs 2, 3, 4, 5 (90% original material by Bohn/Irving), 10

Physics 2130 Labs 1, 2, 3 (90% original material by Bohn/Irving), 4, 5, 6, 7

Workshop Physics II Activity Guide

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Portions of this material have been modified for The University of Toledo by R.G. Bohn and may not have been classroom tested at Dickinson College.

Physics 2070 Labs 1, 6, 7, 8, 12

Physics 2130 Lab 8, 11, Introduction and Computing

Physics 2140 Labs 1, 2, 3, 4, 5, 6, 8

Physics 2080 Labs 1, 2, 3, 4, 5, 7

Tools for Scientific Thinking V1.40

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Physics 2070 Lab 11

Physics 2130 Lab 10

Portions of this experiment are from Pasco's Introductory Optics System Manual (05-8500) and are edited by R.G. Bohn and R. Irving. Used with permission.

Physics 2140 Lab 9

Physics 2080 Lab 8

Portions of this experiment are from Pasco's Introduction Manual and Experiment Guide for the PASCO scientific Model ME-6815 . Used with permission.

Physics 2130 Lab 9

Portions of this experiment are from Vernier's "Physics with Computers", Experiment 29. Used with permission.

Physics 2140 Lab 7

Physics 2080 Lab 6

Physics 2140 Lab 10, Physics 2080 Labs 9 and 10, original material by R.G. Bohn and R. Irving

Appendix A in Physics 2070, 2080,2130, and 2140, original material by R.G. Bohn

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by
David Sokoloff, Ronald Thornton, and Priscilla Laws
(used with permission)

Edited with Contributions by:
R.G. Bohn and R. Irving in 2000
S. Cheng, R. Irving, and M. Brown in 2005
S. Rother in 2008
D. Nero in 2009
A. Lark in 2011
The University of Toledo

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The Laboratory Policies of The Department of Physics and Astronomy

The following is the general policy for the instructional labs offered by the Department of Physics and Astronomy at the University of Toledo.

Grading of Individual Labs

Each laboratory experiment will be graded with a ✓, ✓−, 0, or X. An X indicates that the student was absent. The grading is based on the student's performance throughout the experiment, including the follow-up discussion. Included in the list of relevant performance factors for grading are:

Preparation: *Prior* to attending the lab, **the student should read the experiment in the lab manual** and think about the procedures and the underlying physical principals involved in the experiment. It may be difficult to complete some experiments on time if the student first starts preparing when they enter the lab. At times this may include reading or reviewing a section of the textbook. Students are required to bring their lab manual to every lab session. Failure to bring the lab manual will result in the loss of points.

Involvement: Each student is expected to be actively involved in the experiment. Everyone should take a turn using the equipment because hands-on experience is an important part of the learning process. Each student is also expected to be ready to answer the instructor's questions both during and after the experiment.

Lab Technique: Lab technique includes careful, accurate collection of the data and safe uses of the equipment. Please think about what you are doing. This is an important safety step. While performing each experiment, the student should try to be as accurate as possible, but also be aware that with the equipment provided, some error is to be expected. Any unusual results and/or errors should be noted. Finally, read and record the data to the appropriate number of significant digits.

Analysis and Interpretation: The real purpose of an experiment is *to gain a better understanding of the physics behind the experiment.* When analyzing the data, calculations and graphs are expected to be completed neatly and correctly. The student is expected to discuss the physical principles involved in the experiment as well as the methods of the experiment.

After a group has completed the experiment and analyzed the data, they should notify the lab instructor that they are ready to discuss their work. At the conclusion of the discussion, each student in the group will receive a $\checkmark$,$\checkmark-$, or 0. The $\checkmark$ indicates a reasonable performance in all aspects of the experiment. The $\checkmark-$ indicates that the student had difficulties performing the experiment (excluding equipment failure and similar problems) or that there was a lack of understanding of the physics involved. A *0* indicates that the student did not participate in the experiment or lacked understanding of the concepts involved. Before leaving, the group should make sure the lab station is left in a neat and orderly condition for the next lab section (i.e. discard any scrap paper, clean up any water spilled in the course of the experiment, push chairs under the table, etc.) Failure to clean up after yourself could result in the loss of points.

Grade Reported for the Lab Section

The course syllabus should list the lab as a certain percentage of your course grade. Also, a **minimum of 24 out of a possible 30 points (80%) in the lab is required to pass the lecture/recitation part of the course**. To receive full credit (100%), you must have a score of 30 out of 30 points. Some Lecturers may have different requirements. The lab grade is determined by converting the $\checkmark$, $\checkmark-$, 0, and X into numerical scores.

- ✓ = 2 points
- ✓ – = 1 point
- 0, X = 0 points

Additionally, there are 0–6 "quality points" assigned by the lab instructor based on the student's overall lab performance.

Missed Experiments

In general, labs that are missed cannot be made up. Only under exceptional circumstances will a make-up lab be allowed. If possible, please make your request for a make-up lab during the week of the missed lab so that the equipment will be available. A request for the make-up lab should include supporting documentation and be submitted to the lab instructor and the lab supervisor in a timely manner. For example, if a lab is missed at the beginning of the semester, do not wait until the end of the semester to contact your lab instructor to do a make-up; in most cases, the request will be denied even if supporting documentation is provided.

Repeating the Course

A student who has previously taken the course may not have to retake the lab *if the following are true*:

1. A letter grade (A–F) was received for the course (lecture/quiz/lab). The lab must be retaken if the grade received was an Instructor Withdrawal (IW) or a Withdrawal (W).
2. The previous score for the lab was a 24 or better out of 30 points (80%).
3. The course was taken no more than one calendar year before the present semester.

A student who believes that he/she has fulfilled these requirements should check with the lab supervisor to verify that the above requirements have been met, then must advise his lecturer and present lab instructor—**in writing**—of this situation. Include in this note:

- Your name

- Your student ID number (Rocket number)
- Previous lab section number and instructor's name
- Previous course section number and instructor's name
- Present lab section number and instructor's name
- Present course section number and instructor's name

Providing this information helps insure that credit is properly transferred. The student should confirm that appropriate credit has been given by checking with the instructor.

Lab groups

In general, there will be two (2) people permitted per lab group. Occasionally, two groups may have to cooperate to collect data, but once the data is collected, the groups should separate for the analysis. If there is an odd number of people in the lab section, one group of three (3) will be permitted so that no one is forced to work alone unless they choose to do so. Only when absolutely necessary will more than one group of three be permitted.

Supplies

Although most of the supplies needed to perform the experiment are supplied, items such as the lab manual, pencils, pens, scratch paper, graph paper, rulers, calculators, and other incidentals are to be supplied by the student. Part of preparing for a lab is determining what items are needed.

Missing Lab Instructor

If the lab instructor is more than 5 minutes late, someone should go to the lab supervisor's office (MH 2020) or the main physics office (MH 2017) and ask for assistance. A substitute will be found to get the lab started.

Food

Food, drinks, and tobacco products, including chewing tobacco, *are not permitted* in the lab at anytime.

Safety

Every effort has been made to make the experiments as safe as possible; however, several experiments are potentially dangerous if safety precautions are not followed. Because of this, the student must follow all safety rules prescribed by the instructor or manual. Most of the time, common sense and discretion are the best safety precaution.

Lab 1

Introduction and Computing

Introduction and Computing

If the automobile had followed the same development cycle as the computer, a Rolls-Royce would today cost $100, get a million miles per gallon, and explode once a year, killing everyone inside.

Robert X. Cringely

Objectives

- To understand the goals and procedures of this course.
- To explore the nature of horizontal motion.
- To learn to use some computer programs commonly used in this course.
- To learn to use spreadsheet and graphing software to organize and perform calculations on data and then display it graphically.

Overview

Research and analysis are the basis of all knowledge in the sciences. Scientific research involves a constant interplay between several activities, including observing, reflecting, developing theories, and testing theories with experiment.

Often, before making observations or taking measurements for scientific purposes, a prediction is made of the outcome. Sometimes there's no particular basis for a prediction other than gut feeling; for the purposes of this course, we'll define this type of prediction as a guess. On the other hand, if you are trying to develop a scientific explanation or theory for a phenomenon that has not yet been tested experimentally, scientists would define your prediction as a hypothesis. Many times a prediction is somewhere between a guess and a hypothesis, in the sense that someone has done some reasoning and developed an explanation, but the explanation is not part of a formal scientific theory.

Some areas of research require tedious calculations or the use of mathematical equations that cannot be solved. In these cases, it is convenient—or even necessary—to use a computer. In other cases, computers simply allow us to complete certain tasks much faster then we could by hand. For example, throughout this course you will use a computer to automate the collection of data from a set of motion and force sensors.

Nonetheless, it's important to avoid falling into the trap of thinking of a computer as some kind of mysterious "black box." After all, most—if not all—of the experiments in this book could still be done without the aid of a computer; they would just take longer or require other, specialized equipment.

In this lab, you will complete a few simple experiments that are designed to familiarize you with many of the computational tools that you'll use in this course.

Part I Data Collection And Spreadsheet Use

A key to understanding how to describe motion near the surface of the earth is to observe horizontal motions and vertical motions separately. Eventually, situations in which an object undergoes both horizontal and vertical motion can be analyzed and understood as a combination of these two kinds of basic motions.

Let's start with horizontal motion. How do you think the horizontal position of a bowling ball changes over time as it rolls along on a smooth surface? Assume the effects of friction will be negligible over short distances. For example, suppose you were to roll the ball a distance of 6.0 m on a fairly level smooth floor. Do you expect that the ball would: 1) move at a steady speed, 2) speed up, or 3) slow down? To observe the horizontal motion of a "bowling ball" you can use any large ball. You'll need:

- A ball
- 3 stop watches (accurate to 1/100th of a second)
- A 10 m long tape measure
- Masking tape for marking distances
- A smooth level surface (7 meters in length)
- Computer

Activity 1.1 Horizontal Motion

1. What do you predict will happen to the distance the ball moves as a function of time? Will the ball move at a steady speed, speed up or slow down after it leaves the bowler's hand? Why? **Assume the surface is frictionless.**

2. Find a 7 m length of smooth floor and mark off a starting line and distances of 2 m, 4 m, and 6 m from the starting line. Then:

   a) Roll the ball along the surface three times.

   b) Measure the time it takes to travel 2 m, 4 m, and 6 m.

   c) Record the results in the tables below.

Note: This is a cooperative project. You will need a bowler and three people to time this. Practice several times before recording data in the table below.

Trial 1		Trial 2		Trial 3	
Time [s]	Dist. [m]	Time [s]	Dist. [m]	Time [s]	Dist. [m]
0.00	0.00	0.00	0.00	0.00	0.00

Activity 1.2 Using Computers and Spreadsheets for Calculations

By entering formulas into the computer, a spreadsheet program can perform calculations for you. If you make a mistake and must replace an incorrect number, the spreadsheet program will recalculate everything automatically. Physicists often display and perform calculations on spreadsheets. Thus, spreadsheets can be invaluable tools for data analysis.

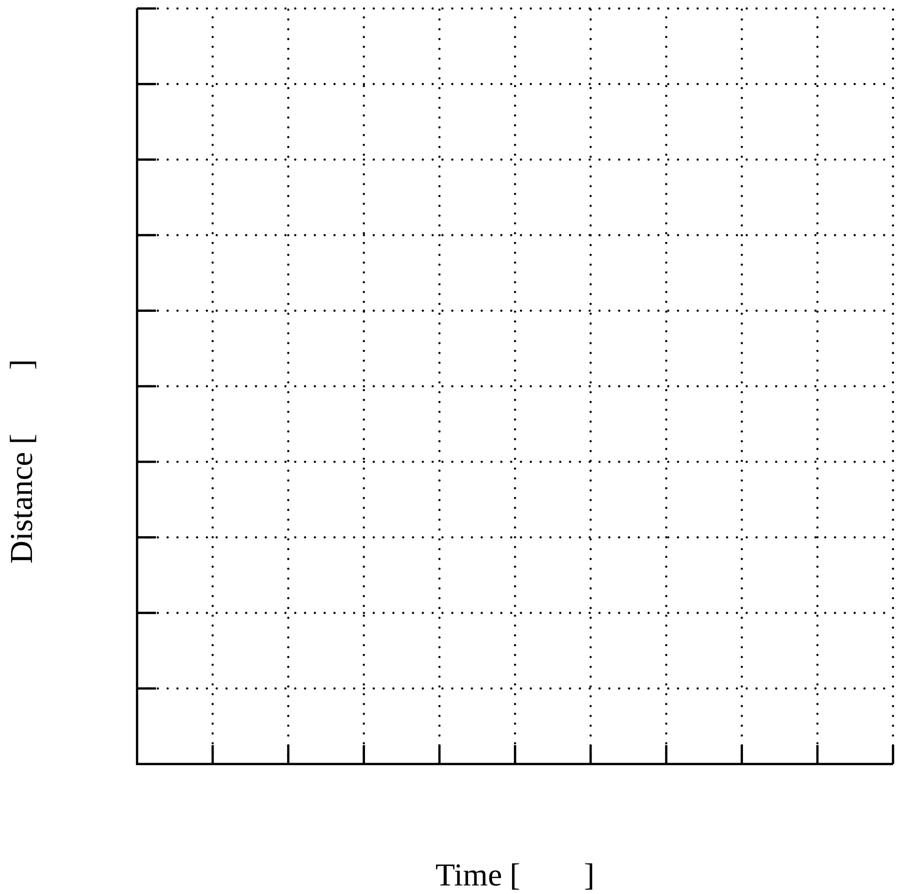
You will now use a spreadsheet to make some calculations from the data you collected in the previous table. Instructions on how to do this will be given to you by your lab instructor. A brief description of spreadsheet modeling is given in Appendix A.

1. Calculate the average speed of the 3 trials, v, in m/s for the ball as it travels the full 6 m distance using *Excel*. Show your result to your lab instructor. Note: you will use *Excel* repeatedly in this course, so take this opportunity to make sure that everyone in your lab group understands how to use it.

Activity 1.3 Drawing a Graph of Distance vs. Time

Now you will graph your data for the distance your ball traveled as a function of the rolling-time of the ball. This graphing should be done both by hand and on the computer.

1. Fill in the units and the scale numbers in the graph below and plot the data you collected by hand. You should plot a fourth data point on your graph by including the (0,0) point.



2. Use the computer to create the same graph in *Excel*. Write down the best fit line equation below, and show the graph to your instructor. To get the best fit line, right click on a data point, and add a *trend line*. Under *options*, set the intercept to 0 and include the equation.

Activity 1.4 Mathematical Relationships

We are interested in the mathematical nature of the relationship between distance and time for rolling on a level surface. Some definitions of mathematical relationships are shown in the sketches below.

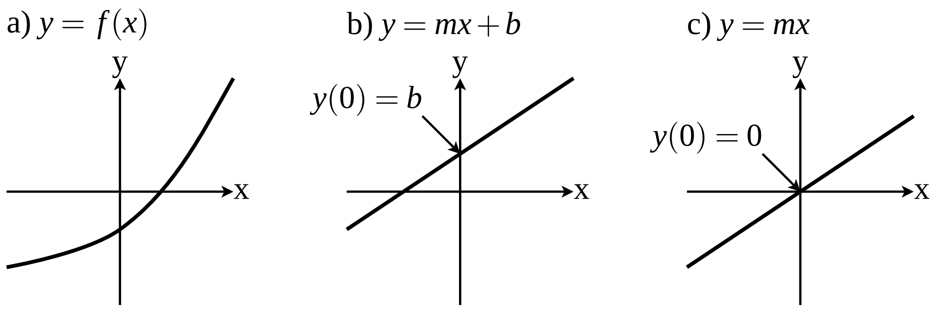


Figure 1.1: Case (a): y increases with x. Case (b): y increases with x and is a linear function of x. Case (c): y increases with x, is a linear function of x, and is proportional to x.

1. By comparing the shape of the graph you have just produced with the sketches shown above, would you say that the distance, x, increases with time, t? Decreases with t? Is it a *linear function* of t? Is it *proportional* to t? Explain.

2. How do the results compare with the prediction you made in Activity Activity 1.1? Were you surprised?

3. What do you think would happen to the slope, m, of the graph, if the ball had been rolled faster? Would it increase? Decrease? Stay the same?

Part II Introduction To Data Analysis With Excel

For this short experiment, you will measure the periods for a pendulum of various lengths. Then you will plot the period versus the lengths in several ways and try to find the relation between the period and the length by fitting a curve to the data. You will need:

- Photogate
- Pendulum
- Meter stick
- Computer

Activity 2.1 The Period of a Pendulum

1. Set up a simple pendulum that you will use to gather data. Then, set up the photogate to gather data on the period of a pendulum. The pendulum, when at rest, should block the photogate reliably. The photogate should be connected to *Dig/Sonic 1* of the *LabPro*. Open the file “Pendulum Timer” with the *LabPro* software; there is a shortcut from the Desktop.

2. Can you predict a relationship between the length of the pendulum and the period? If so, what do you predict?

3. Now, you are ready to begin collecting data. For each length, you will need to record the period. Gather five periods and lengths for the pendulum. Do your best to measure the period several times and take the average. Wait for the periods to become stable before take the readings. Make sure to keep the ends of the string apart and hold them steady, so the period does not decay.

Length [m]	Period [s]

4. With the data collected, you are ready to plot the data. Use *Excel* to do this. You are going to attempt to determine the relationship between the length and the period. The easiest way to do this is to first plot length vs. period. Do these points show a trend? To determine the relationship, plot other things, until you get a straight line. You should try:

   - T vs. l
   - T vs. l^2
   - T^2 vs. l

5. Which fit gave you a straight line? What does this say about the relationship between the length and period? Write down the correlation coefficients for all three graphs (you can get these by adding linear trend lines).

6. There is a constant in the relationship between the length and the period. Can you figure out what the constant is? Write down the equation for the relationship between period and length, including the constants, using symbols.

Lab 2

Introduction to Motion

Pre-Lab: Introduction to Motion

Name:________________________ Section:______

1. In this lab, you will walk towards and away from a motion sensor while it measures your position and velocity. Assume that the positive *x*-axis points away from the motion sensor, and that the origin is at the sensor.

   a) If you walk towards the motion sensor is your velocity positive or negative. What about your speed?

   b) You continue walking towards the motion sensor. Is your position (displacement) positive or negative?

2. If you were given a graph of the position of an object versus time, how would you determine the object's velocity?

3. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity. (For example: "*In the first activity, we will create a series of four distance-time graphs corresponding to different constant velocities*.")

4. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Introduction to Motion

Never mistake motion for action.

Ernest Hemingway

Objectives

- To discover how to measure motion with a motion detector
- To see how motion looks as a distance (position)-time graph
- To see how motion looks as a velocity-time graph
- To discover the relationship between position-time and velocity-time graphs.

Overview

In this unit you will examine two different ways that the motion of an object can be represented graphically. You will use a motion detector to plot distance (position) and velocity-time graphs of the motion of your own body and a cart. The study of motion and its mathematical and graphical representation is known as *kinematics*.

Comment:

"Distance" is short for "distance from the motion detector." The motion detector is the origin from which distances are measured. It detects the closest object directly in front of it (including your arms if you swing them as you walk). It will not correctly measure anything closer than 0.5 m. **When making your graphs don't get closer than 0.5 m from the motion detector.**

Part I Distance-Time Graphs of Your Motion

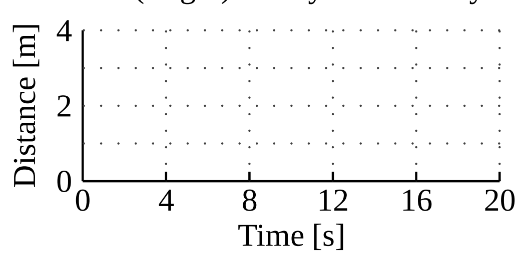
How does a distance-time graph look when you move slowly? Quickly? What happens when you move toward the motion detector? Away? After completing this part of the lab, you should be able to look at a distance-time graph and describe the motion of an object. You should also be able to look at the motion of an object and sketch a graph representing that motion. You will need the following materials:

- Computer
- Motion detector
- Meter stick

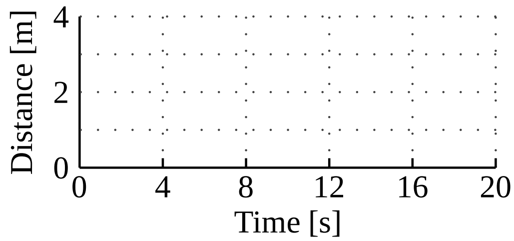
Activity 1.1 Making Distance (Position)-Time Graphs

1. Open the data acquisition program. To start, open the file *Introduction-_to_Motion_A1-1.exp*. The distance vs. time axes should appear on the screen. (Be sure the data acquisition hardware is connected to the computer and turned on, and the motion detector is plugged into *Dig/Sonic 2*.)
2. When you are ready to start graphing distance, click once on the *Start* button in the top left-hand corner of the screen.
3. Make distance-time graphs for different walking speeds and directions, and sketch your graphs on the axes. Change the maximum time on the *x*-axis if necessary.

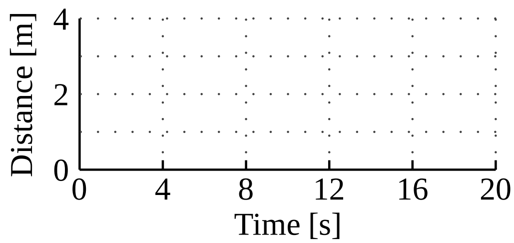
   a) Start at the 0.5 m mark and make a distance-time graph, walking away from the detector (origin) slowly and steadily.



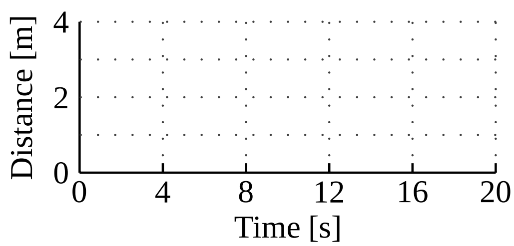
   b) Make a distance-time graph, walking away from the detector (origin) medium fast and steadily.



c) Make a distance-time graph, walking toward the detector (origin) slowly and steadily.



d) Make a distance-time graph, walking toward the detector (origin) medium fast and steadily.



4. Describe the difference between the graph you made by walking away slowly and the one made by walking away quickly.

5. Describe the difference between the graph made by walking toward and the one made walking away from the motion detector.

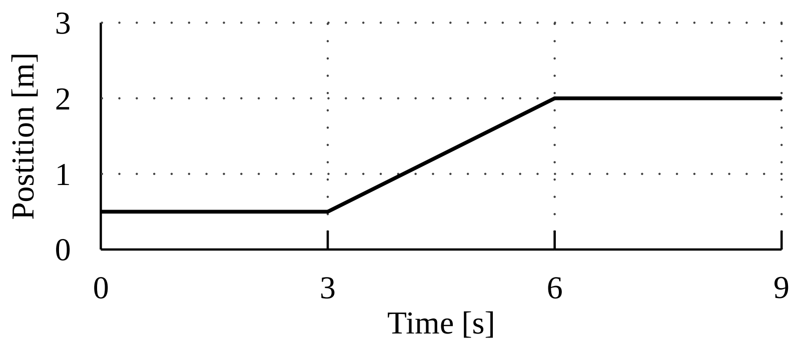
Comment:

It is common to refer to the distance of an object from some origin as the position of the object. Since the motion detector is at the origin of the coordinate system, it is better to refer to the graphs you have made as *position-time* graphs. From now on you will plot position-time graphs.

Activity 1.2 Matching a Position Graph

By now you should be pretty good at predicting the shape of a graph of your movements. Can you do things the other way around by reading a position-time graph and figuring out how to move to reproduce it? In this activity you will match a position-time graph shown on the computer screen.

1. Open the experiment file called *Introduction_to_Motion_A1-2.exp* (*Position Match)*. A position-time graph like that shown below will appear on the screen.



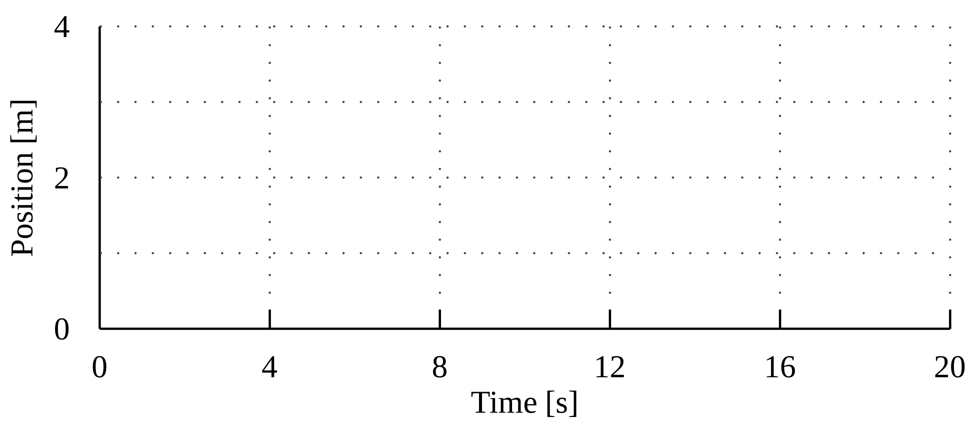
2. Move to match the *Position Match* graph on the computer screen. You may try a number of times. It helps to work in a team. Get the times right. Get the positions right. Each person should take a turn.

3. What was the difference in the way you moved to produce the two differently sloped parts of the graph you just matched?

Activity 1.3 Other Position-Time Graphs

It will be less confusing if you remove the *Position Match* graph from the screen before doing the exercises below. To do this, select *New* under *File* and reload *Introduction_to_Motion_A1-1.exp*.

1. Sketch your own position-time graph on the axes which follow with a dashed line. Use straight lines, no curves. Now see how well someone in your group can duplicate this graph on the screen by walking in front of the motion detector. Don't just stand still, you must move back and forth.



2. Draw the best attempt by a group member to match your position-time graph on the same axes. Use a solid line.

Part II Velocity-Time Graphs of Motion

You have already plotted your position as a function of time. Another way to represent your motion during an interval of time is with a graph which describes how fast and in what direction you are moving. This is a *velocity-time* graph. Velocity is the rate of change of position with respect to time. It is a quantity which takes into account your speed (how fast you are moving) and also the direction you are moving. Thus, when you examine the motion of an object moving along a line, its velocity can be positive or negative meaning the velocity is in the positive or negative direction.

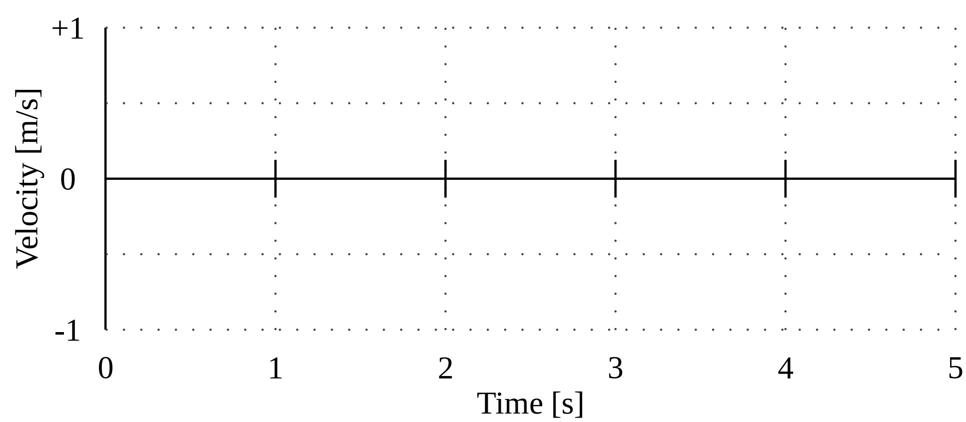
Graphs of velocity over time are more challenging to create and interpret than those for position. A good way to learn to interpret them is to create and examine velocity-time graphs of your own body motions, as you will do in this part of the lab.

Activity 2.1 Making Velocity Graphs

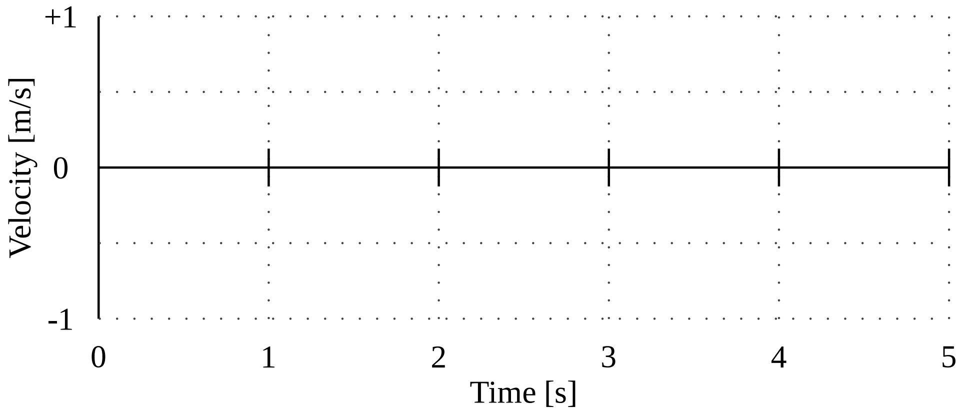
1. Set up to graph velocity. Open the experiment *Introduction_to_Motion-_A2-1.exp (Velocity Graphs)* and set up the *Velocity* axis to read from -1 to 1 m/sec and the *Time* axis from 0 to 5 sec, as shown in the next figures.

2. Graph your velocity for different walking speeds and directions, and sketch your graphs on the axes. (Just draw smooth patterns; leave out smaller bumps that are mostly due to your steps.)

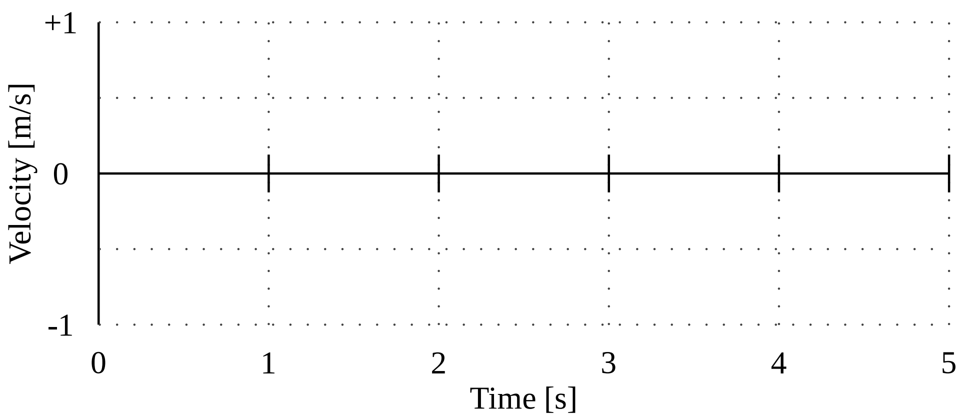
   a) Make a velocity-time graph by walking away from the detector slowly and steadily. Try again until you get a graph you're satisfied with. You may want to change the velocity scale so that the graph fills more of the screen and is clearer. To do this, click the mouse once with the cursor pointing to the maximum axis reading. Type in the new value and hit return. Then sketch your graph on the axes below.



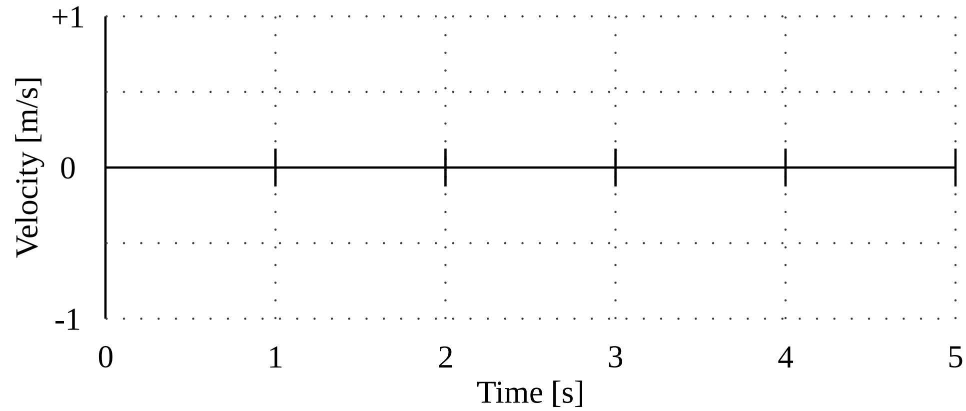
   b) Make a velocity-time graph, walking away from the detector medium fast and steadily.



c) Make a velocity-time graph, walking toward the detector slowly and steadily.



d) Make a velocity-time graph, walking toward the detector medium fast and steadily.

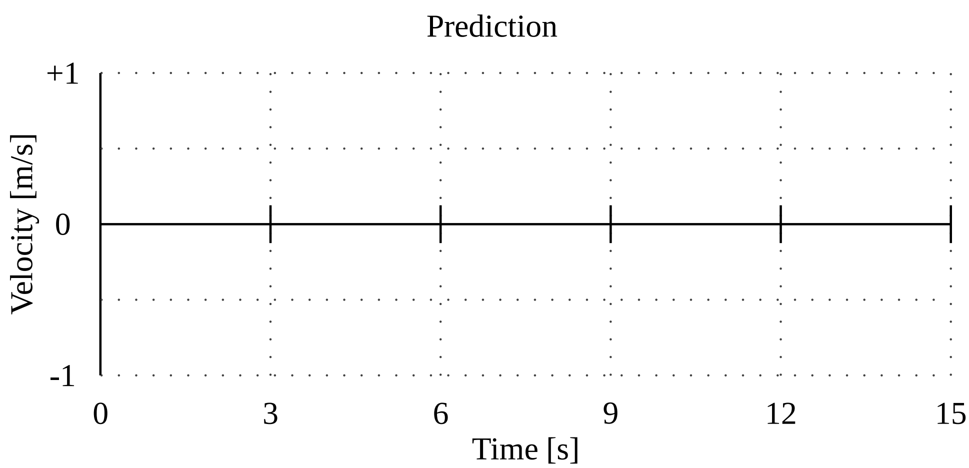


3. What is the most important difference between the graph made by slowly walking away from the detector and the one made by walking away more quickly?

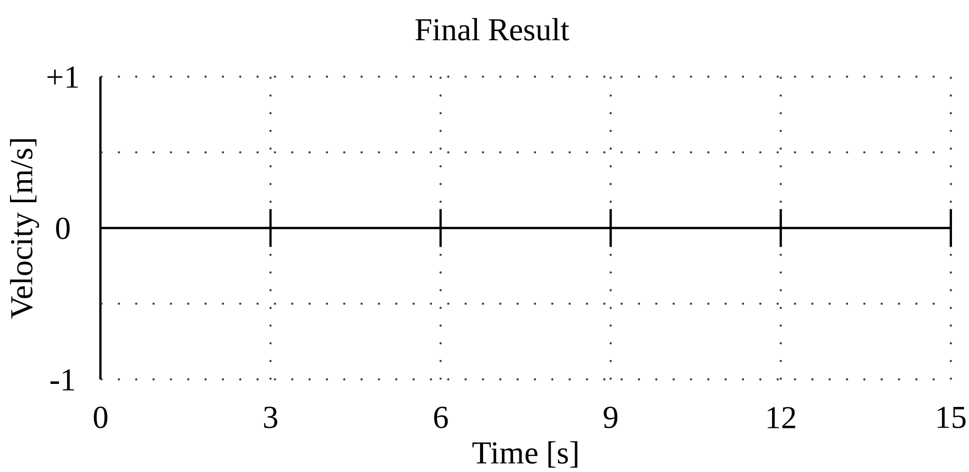
4. How are the velocity-time graphs different for motion away and motion toward the detector?

5. Each person should draw below, using a dashed line, your prediction of the velocity-time graph produced if you: 1) Walk away from the detector slowly and steadily for about five seconds, 2) stand still for about five seconds, and then 3) walk toward the detector steadily about twice as fast

as before. Compare your predictions and see if you can all agree. Use a solid line to draw in your group prediction.



6. Test your prediction. (Be sure to adjust the time scale to 15 seconds. As before. this can be done by clicking the mouse once on the 5 to highlight it, typing in a 15 and then hitting the return key.) Repeat your motion until you think it matches the description. Draw the best graph on the following axes. **Be sure the five second stop shows clearly.**



7. Sketch below velocity vectors representing the three parts of the motion described in Step 5.

a) Walking slowly away from the detector:

b) Standing still:

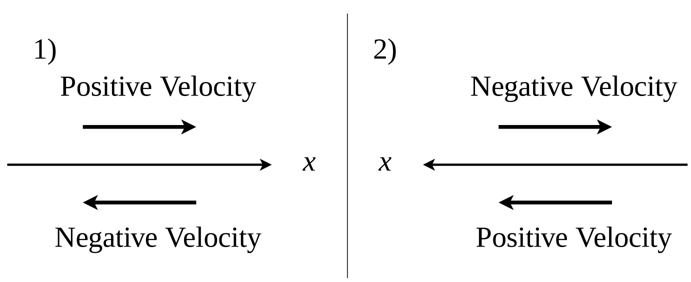
c) Walking rapidly toward the detector:

Comment:
Velocity implies both speed and direction. How fast you move is your speed; the rate of change of position with respect to time. As you have seen, for motion along a line (e.g., the positive *x*-axis) the sign (+ or -) of the velocity indicates the direction. If you move away from the detector (origin), your velocity is positive, and if you move toward the detector, your velocity is negative. The faster you move away from the origin, the larger your positive velocity is. The faster you move toward the origin, the "larger" your negative velocity is. That is -4 m/s is twice as fast as -2 m/s, and both motions are toward the origin. These two ideas of speed and direction can be combined and represented by vectors. A velocity vector is represented by an arrow pointing in the direction of motion. The length of the arrow is drawn proportional to the speed; the longer the arrow, the larger the speed. If you are moving toward the right, your velocity vector can be represented by the arrow shown below.

If you were moving twice as fast toward the right, the arrow representing your velocity vector would look like

while moving twice as fast toward the left would be represented by the following arrow

What is the relationship between a one-dimensional velocity vector and the sign of velocity? This depends on the way you choose to set the positive *x*-axis.



In both diagrams above, the top vectors represent velocity toward the right. In diagram 1, the *x*-axis has been drawn so that the positive *x*-direction is toward the right, as it is usually drawn. Thus the top arrow represents positive velocity. However, in diagram 2, the positive *x*-direction is toward the left. Thus the top arrow represents negative velocity. Likewise, in both diagrams the bottom arrows represent velocity toward the left. In diagram 1 this is negative velocity, and in diagram 2 it is positive velocity.

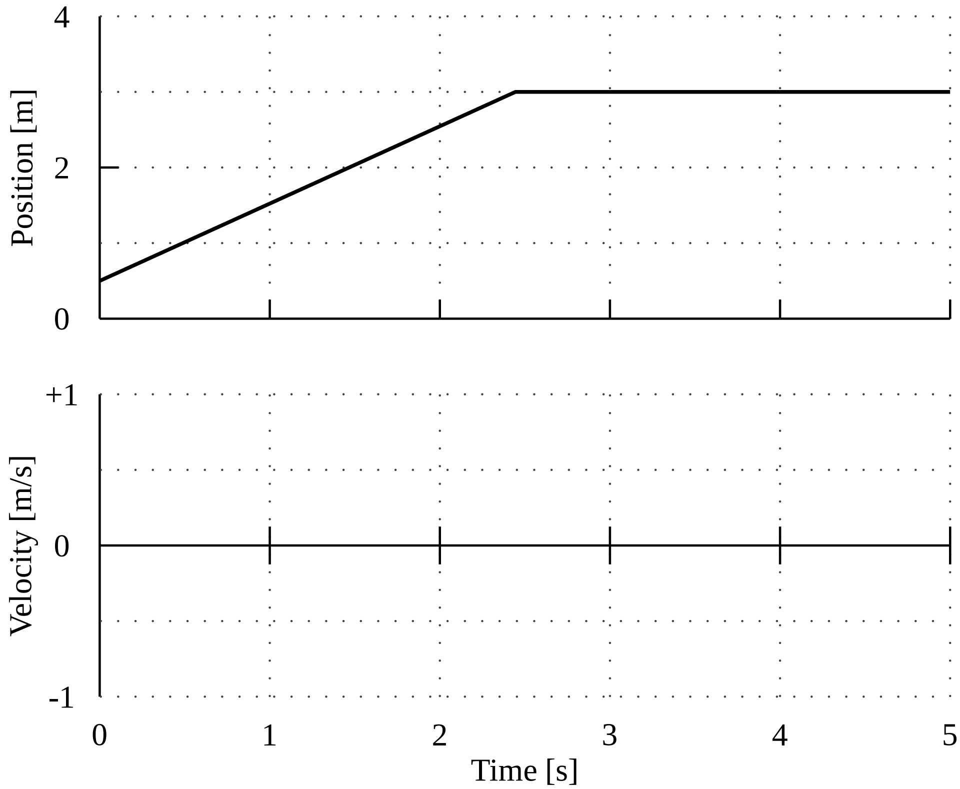
Part III Relating Position and Velocity Graphs

You have looked at position and velocity-time graphs separately. Since position-time and velocity-time graphs are different ways to represent the same motion, it ought to be possible to figure out the velocity at which someone is moving by examining her/his position-time graph. Conversely, you ought to be able to figure out how far someone has traveled (change in position) from a velocity-time graph.

Activity 3.1 Predicting Velocity Graphs from Position Graphs

1. Set up to graph Position and Velocity. Open the experiment *Introduction-_to_Motion_A3-1 (Velocity from Position)* to set up the top graph to display *Position* from 0 to 4 m for a time of 5 s, and the bottom graph to display *Velocity* from -1 to 1 m/s for 5 s. Clear any previous graphs.

2. Predict a velocity-time graph from a position-time graph. Carefully study the position-time graph shown below and predict the velocity-time graph that would result from the motion. Using a dashed line, sketch your prediction of the corresponding velocity-time graph on the velocity axes.



3. Test your prediction. After each person has sketched a prediction, Start, and do your group's best to make a position graph like the one shown. Walk as smoothly as possible. When you have made a good duplicate of the position graph, sketch your actual graph over the existing position-time graph. Use a solid line to draw the actual velocity graph on the same graph with your prediction. (Do not erase your prediction).

4. How would the *position-time* graph be different if you moved faster? Slower?

5. How would the *velocity-time* graph be different if you moved faster? Slower?

Comment:

Average velocity during a particular time interval can also be calculated as the change in position divided by the change in time. The change in position is often called the displacement. By definition, this is also the slope of the position-time graph for that time period. As you have observed, the faster you move, the more inclined is your position-time graph. The slope of a position-time graph is a quantitative measure of this incline, and therefore it tells you the velocity of the object.

Activity 3.2 Calculating Average Velocity

In this activity, you will find an average velocity from your velocity-time graph in Activity 3.1 and then from your position-time graph.

1. Find your average velocity from your *velocity-time* graph in Activity 3.1. Select the *x=? button* on the toolbar and read a number of values (say ten) from the portion of your velocity-time graph where your velocity is relatively constant, and use them to calculate the average (mean) velocity. Write the 10 values in the table below.

Velocity Values [m/s]

1		6	
2		7	
3		8	
4		9	
5		10	

Average value of the velocity:______ m/s

2. Calculate your average velocity from the slope of your *position-time* graph in Activity 3.1. Use the *x=? button* to read the position and time coordinates for two typical points while you were moving. (For a more accurate answer, use two points as far apart as possible but still typical of the motion, and within the time interval over which you took velocity readings.)

	Position [m]	Time [s]
Point 1		
Point 2		

Calculate the change in position (displacement) between points 1 and 2. Also calculate the corresponding change in time (time interval). Divide the change in position by the change in time to calculate the average velocity. Show your calculations below.

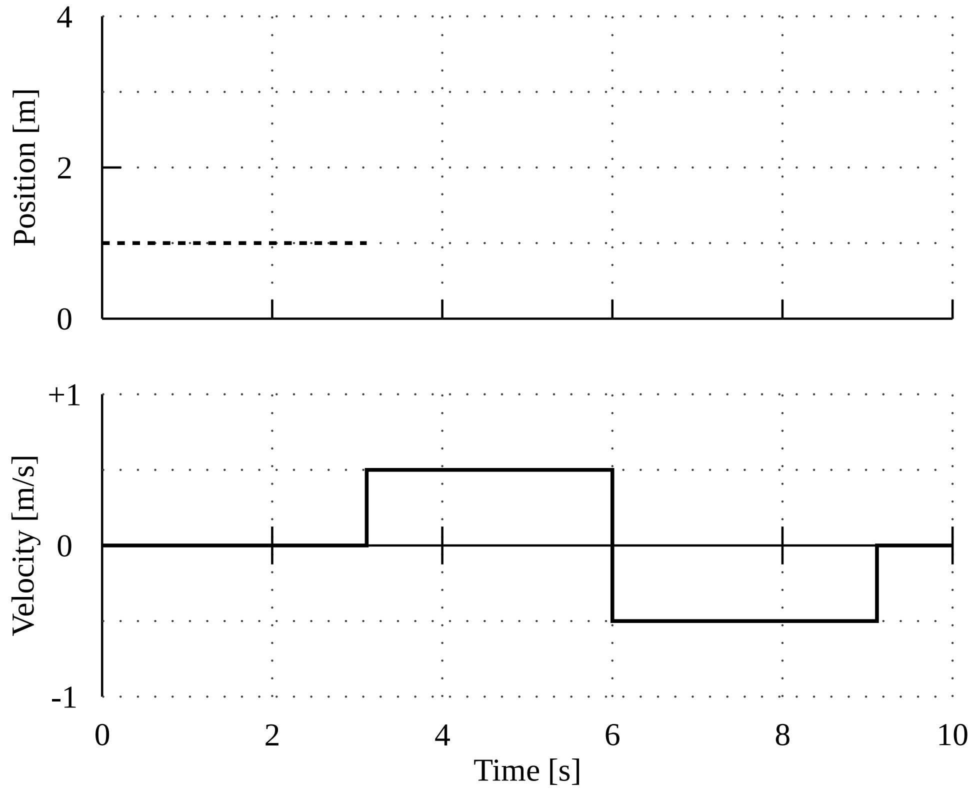
Change in Position [m]	
Time Interval [s]	
Average Velocity [m/s]	

3. Is the average velocity positive or negative? Is this what you expected?

4. Does the average velocity you just calculated from the position-time graph agree with the average velocity you found from the velocity-time graph? Do you expect them to agree? How would you account for any differences?

Activity 3.3 Predicting Position Graphs from Velocity Graphs

1. Carefully study the velocity-time graph shown below. Using a dashed line, sketch your prediction of the corresponding position-time graph on the top set of axes. (Note that you start at the 1 meter mark.)



2. Test your prediction. Reset the *Time* axis to 0–10 s before you start.

3. After each person has sketched a prediction, do your group's best to duplicate the bottom (velocity-time) graph by walking. Be sure to graph velocity first. When you have made a good duplicate of the velocity-time graph, draw your actual result over the existing velocity-time graph.

4. Use a solid line to draw the actual position-time graph on the same axes with your prediction. (Do not erase your prediction.)

5. How can you tell from a *velocity-time* graph that the moving object has changed direction?

6. What is the velocity at the moment the direction changes?

7. Is it possible to actually move your body (or an object) to make vertical lines on a *position-time* graph? Why or why not? What would the velocity be for a vertical section of a position-time graph?

8. How can you tell from a *position-time* graph that your motion is steady (motion at a constant velocity)?

9. How can you tell from a *velocity-time* graph that your motion is steady (constant velocity)?

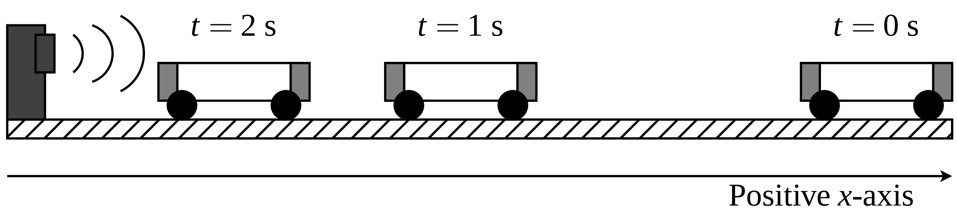
Lab 3

Changing Motion

Pre-Lab: Changing Motion

Name:______________________________ Section:______

1. The diagram below shows the positions of a cart at equal time intervals as it *moves toward* a motion sensor and *slows down* (in lab, you will simulate this by pushing the cart up a ramp). At each indicated time, sketch a vector (an arrow) above the cart that represents the velocity vector of the cart at that time.



2. Show below how you would find the vector representing the change in velocity between the times 1 s and 2 s in the diagram above. Do this graphically by sketching the appropriate vectors. Based on the direction of this vector and the direction of the positive x-axis, what is the sign of the acceleration?

3. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

4. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Changing Motion

A cheetah can accelerate from 0 to 50 miles per hour in 6.4 seconds.

Encyclopedia of the Animal World

A Jaguar can accelerate from 0 to 50 miles per hour in 6.1 seconds.

World Cars

Objectives

- To understand the meaning of the magnitude and direction of acceleration
- To discover the relationship between velocity and acceleration graphs
- To learn how to represent velocity and acceleration using vectors

Overview

In the previous lab, you looked at *position-time* and *velocity-time* graphs of the motion of your body. The data for the graphs were collected using a motion detector. Your goal in this unit is to learn how to describe various kinds of motion in more detail. It is not enough when studying motion in physics to simply say that "the object is moving toward the right" or "it is standing still."

You have probably realized that a velocity-time graph is better than a position-time graph when you want to know how fast and in what direction you are moving at each instant in time as you walk. When the velocity of an object is changing, it is also important to know how it is changing. The rate of change of velocity with respect to time is known as the *acceleration*.

In order to get a feeling for acceleration, it is helpful to create and learn to interpret *velocity-time* and *acceleration-time* graphs for some relatively simple motions of a cart on a track. You will be observing the cart with a motion detector as it moves with constantly changing velocity.

Part I Velocity-Time And Acceleration-Time Graphs

In this part of the lab you will be asked to predict and observe the shapes of velocity-time and acceleration-time graphs of a cart moving along a track. You will focus on cart motions with a steadily increasing velocity. You will need the following materials:

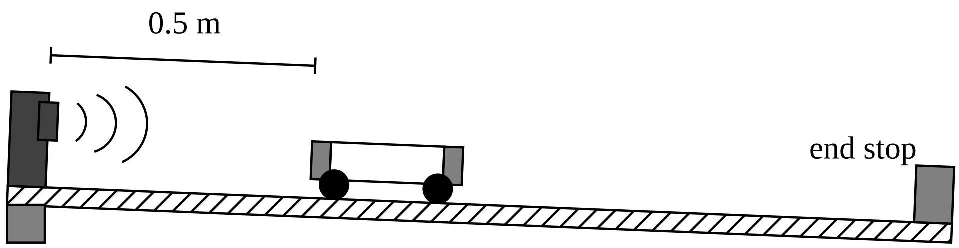
- Computer
- Motion detector
- Cart
- Track with end stop
- Block to elevate track

Activity 1.1 Speeding Up

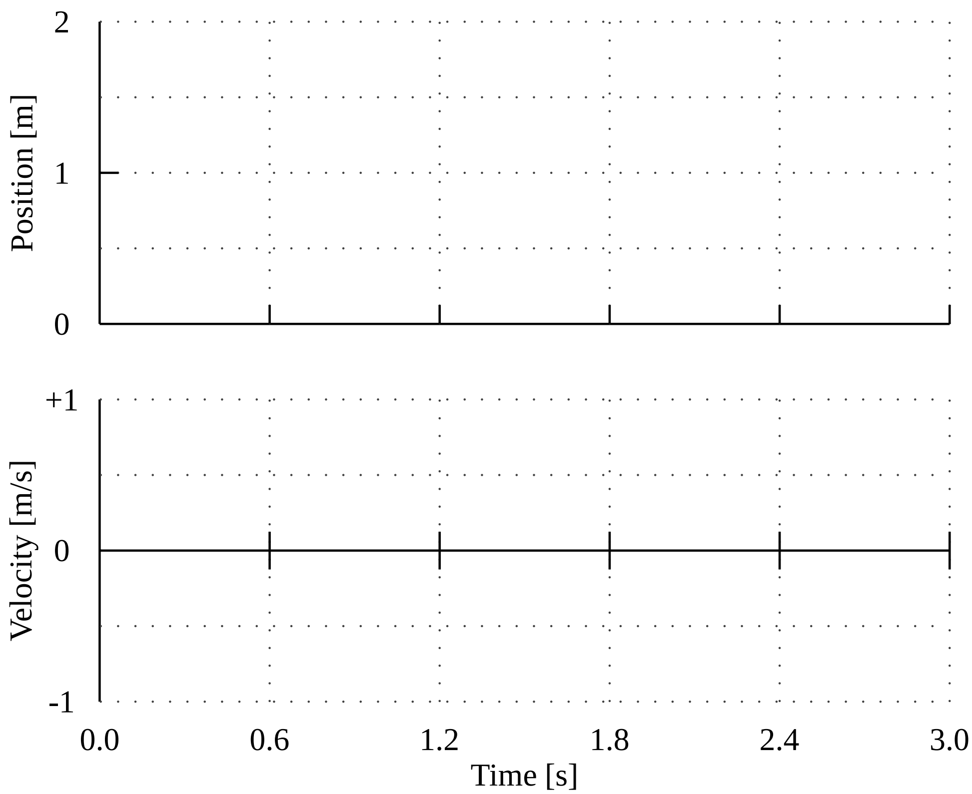
In this activity you will look at velocity-time and acceleration-time graphs of the motion of a cart when its velocity is changing. You will be able to see how these two representations of the motion are related to each other when the cart is speeding up.

1. Set up the cart on the track as shown in the following figure. Elevate the motion detector end of the track with a block. You may need to tilt the

detector slightly to make sure that it can "see" the cart all the way to the end of track.



2. Open the experiment *Changing_Motion_A1-1.exp* (*Speeding Up*) to display a two graph layout with *Position* from 0 to 2.0 m and *Velocity* from -1.0 to 1.0 m/s for a time interval of 3.0 s as shown below.



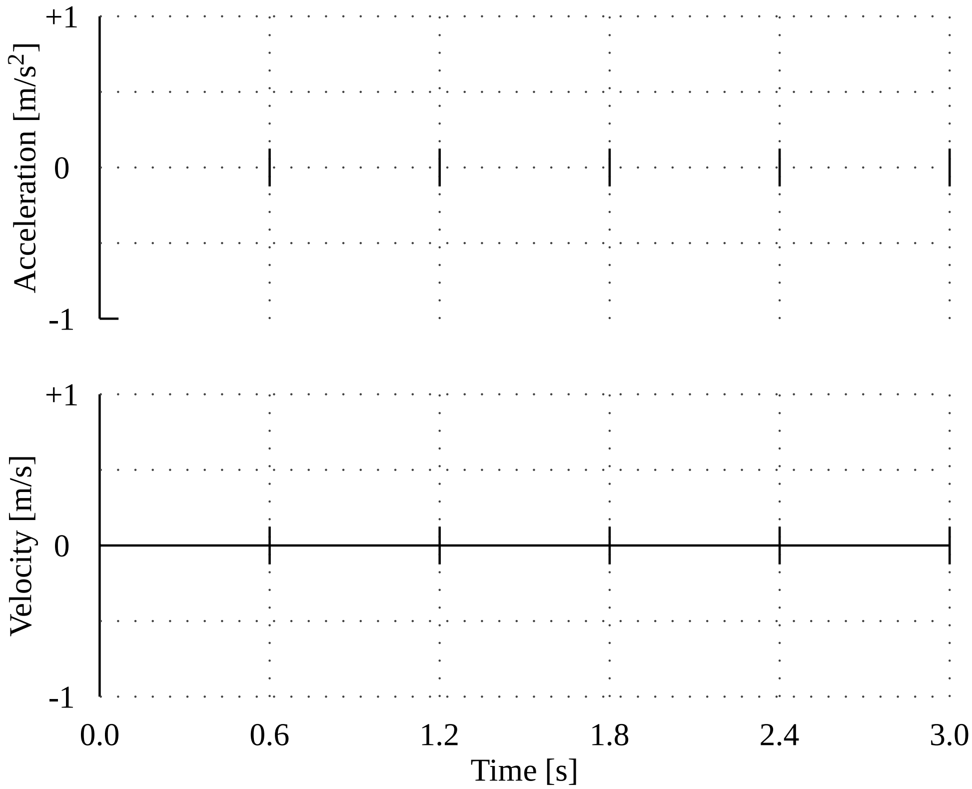
3. Hold the cart, click *Start* to start graphing, and when you hear the clicks of the motion detector, release the cart from rest. Do not put your hand

between the cart and the detector. **Be sure to stop the cart before it hits the end stop.** Repeat, if necessary, until you get a nice set of graphs. Change the position and velocity scales if necessary so that the graphs fill the axes.

4. Is the position-time graph a straight line? Is the velocity-time graph a straight line? How is velocity related to the *position-time* graph of an object moving in one-dimension?

Activity 1.2 Velocity and Acceleration of a Cart That Is Speeding Up

1. Open the experiment *Changing_Motion_A1*-2. You should have a set of axes similar to the set below. Repeat the previous experiment with the inclined track. Sketch the velocity-time and acceleration-time graphs below. Correct the scales if necessary.



Comment:

Average acceleration during a particular time period is defined as the average rate of change of velocity with respect to time (the change in velocity divided by the change in time). By definition, the rate of change of a quantity graphed with respect to time is also the slope of the curve. Thus, the (average) slope of an object's velocity-time graph is also the (average) acceleration of the object.

2. Find the average acceleration of the cart from your *acceleration-time* graph. Select *x=?* from the *Menu Bar* to read a number of values (say ten) of the acceleration. (Only use values from the portion of the graph after the cart was released and before the cart was stopped, where the acceleration is not zero.)

Acceleration Values [m/s^2]

Average acceleration: _________m/s^2

3. Calculate the slope of your *velocity-time* graph. Use *x=?* to read the velocity and time coordinates for two typical points on the velocity graph. (For a more accurate answer, use two points as far apart in time as possible but still during the time the cart was speeding up.)

	Velocity [m/s]	Time [s]
Point 1		
Point 2		

Calculate the change in velocity between points 1 and 2. Also calculate the corresponding change in time (time interval). Divide the change in velocity by the change in time. This is the average acceleration. Show your calculations below.

Speeding Up Change in velocity [m/s]	
Time interval [s]	
Average acceleration [m/s^2]	

4. Is the acceleration positive or negative? Is this what you expected?

5. Does the average acceleration you just calculated agree with the average acceleration you found from the acceleration-time graph? Do you expect them to agree? How would you account for any differences?

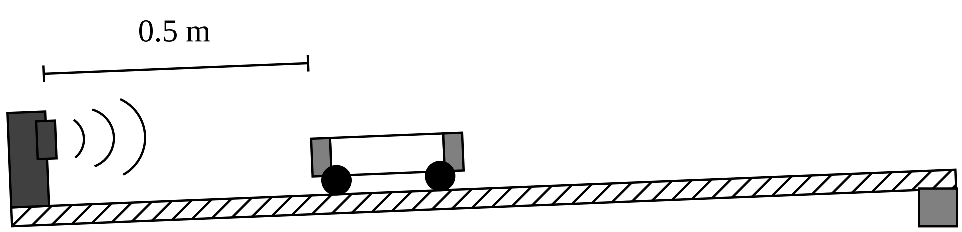
Part II Slowing down and Speeding Up

In this part of the lab, you will first look at a cart moving up an incline and slowing down. A car driving down a horizontal road and being brought to rest by applying the brakes is a good example of this type of motion. Later, you will examine the cart moving toward the motion detector and speeding up. In both cases, we are interested in the shapes of the velocity-time and acceleration-time graphs, as well as the vectors representing velocity and acceleration.

Activity 2.1 Slowing Down

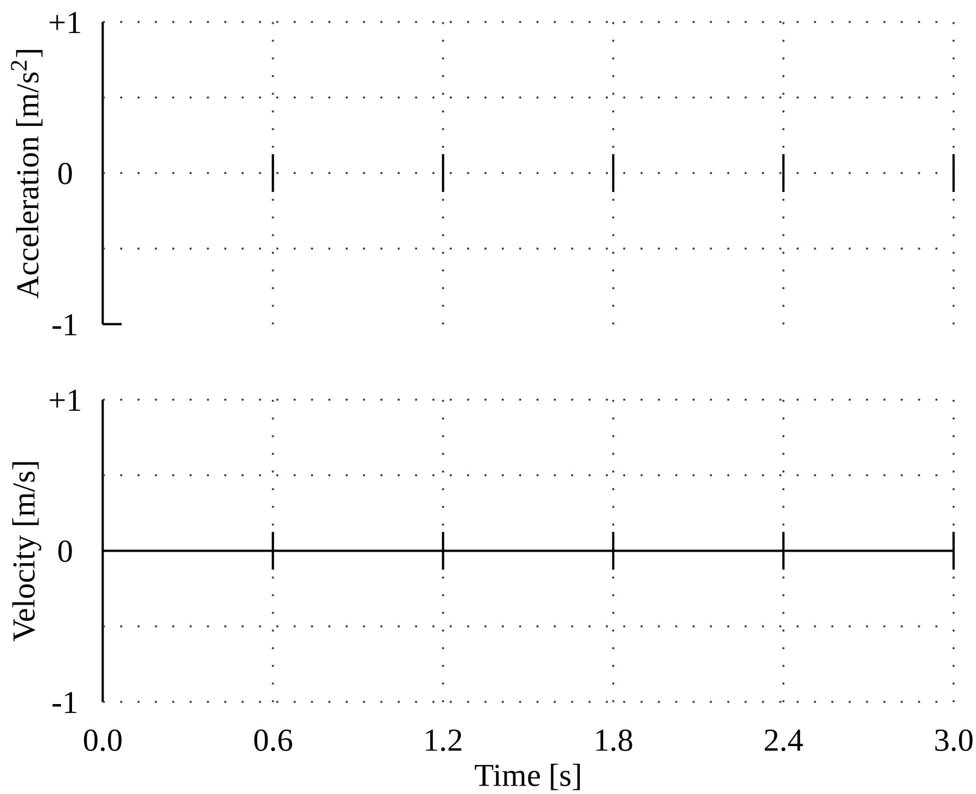
In this activity you will look at the velocity-time and acceleration-time graphs of the cart when it is *moving away* from the motion detector and *slowing down*.

1. Incline the track so that the motion detector is at the bottom. Make sure that the incline is the same as in Activity 1.1. Now, when you give the cart a push away from the motion detector, it will slow down after it is released.

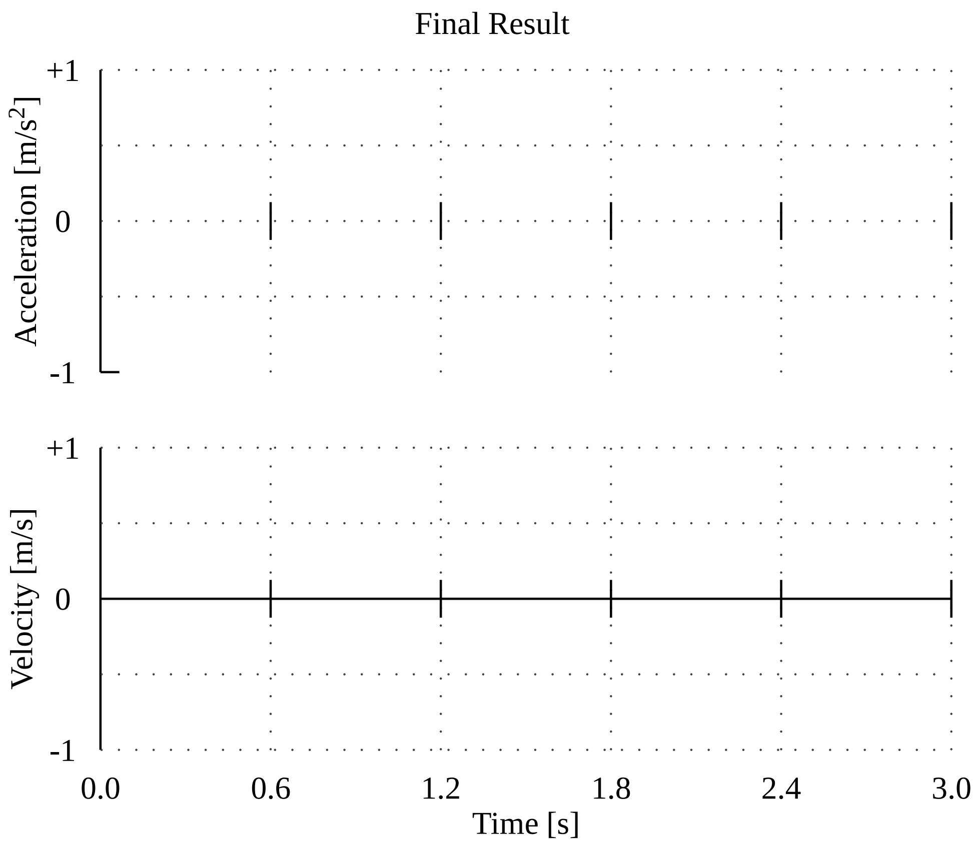


2. If you give the cart a push away from the motion detector and release it, will the acceleration be positive, negative or zero (after it is released)? Sketch your predictions for the velocity-time and acceleration-time graphs on the axes below.

Prediction



3. Now test your prediction. Start with the back of the cart near the 0.5 meter mark. When you begin to hear the clicks from the motion detector, give the cart a gentle push away from the detector so that it comes to a stop near the end of the incline. Be sure that your hand is not between the cart and the detector. **Stop the cart—do not let it return toward the motion detector.** You may have to try a few times to get a good run. Don't forget to change the scales if this will make your graphs easier to read.



4. Neatly sketch your results on the axes above. Label your graphs with:

   - "A" at the spot where you started pushing.
   - "B" at the spot where you stopped pushing.
   - "C" at the spot where the cart stopped moving.

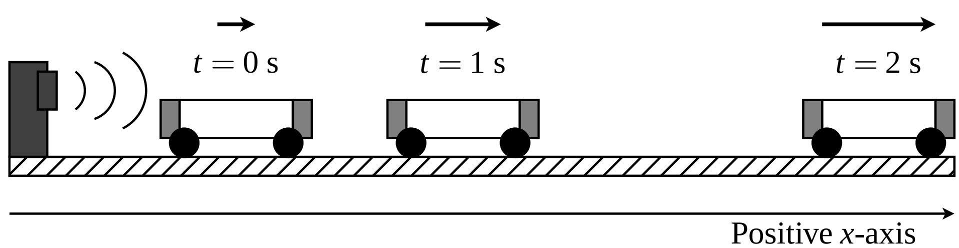
   Also sketch on the same axes the velocity-time and acceleration-time graphs from Activity 1.2.

5. Did the shapes of your velocity-time and acceleration-time graphs agree with your predictions? How can you tell the sign of the acceleration from a *velocity-time* graph?

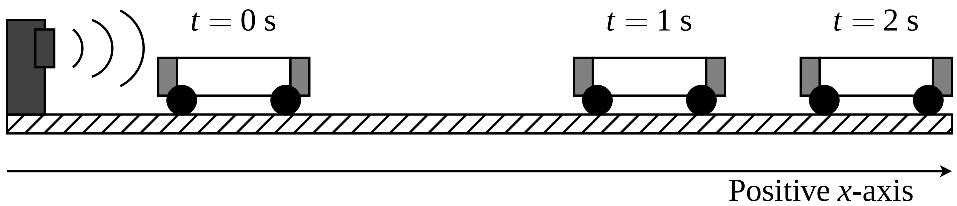
6. How can you tell the sign of the acceleration from an *acceleration-time* graph?

7. Is the sign of the acceleration what you predicted? How does *slowing down* while *moving away* from the detector result in this sign of acceleration? Hint: remember that acceleration is the rate of change of velocity with respect to time. Look at how the velocity is changing.

8. The diagrams below show the positions of the cart at equal time intervals. At each indicated time, you can sketch a vector (arrow) above the cart to represent its instantaneous velocity. As an example, for a cart that is *moving away* from the detector and *speeding up*, you would have a diagram that looks like:



In following diagram, you should sketch vectors to represent the velocity of a cart that is *moving away* from the motion detector and *slowing down*.



9. Show below how you could graphically find the vector representing the change in velocity (i.e. the acceleration vector) between the times 1 s and 2 s in the diagram above. Remember that the change in velocity is the final velocity minus the initial velocity. You need to draw the vectors.

10. Based on the direction of this vector and the direction of the positive *x*-axis, what is the sign of the acceleration? Does this agree with your answer to Step 7?

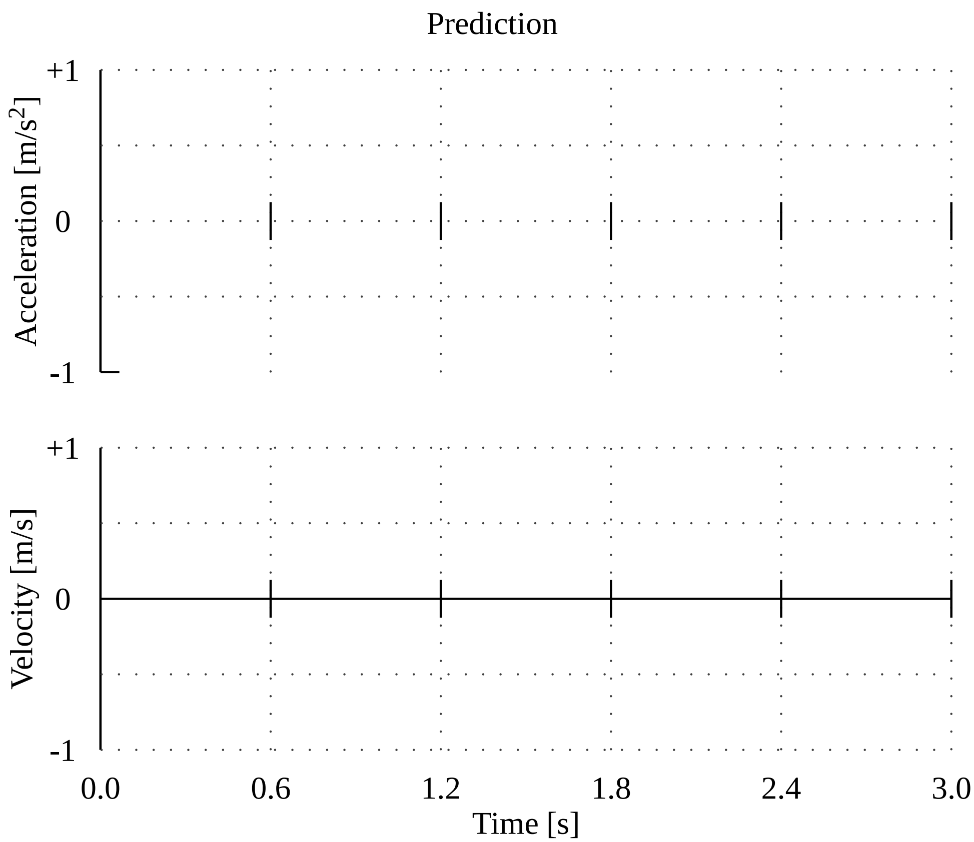
11. Based on your observations in this Activity, find a general rule to predict the sign of the acceleration if you know the sign of the velocity (i.e. the direction of motion) and whether the object is speeding up or slowing down.

	Towards	Away
Speeding Up		
Slowing Down		

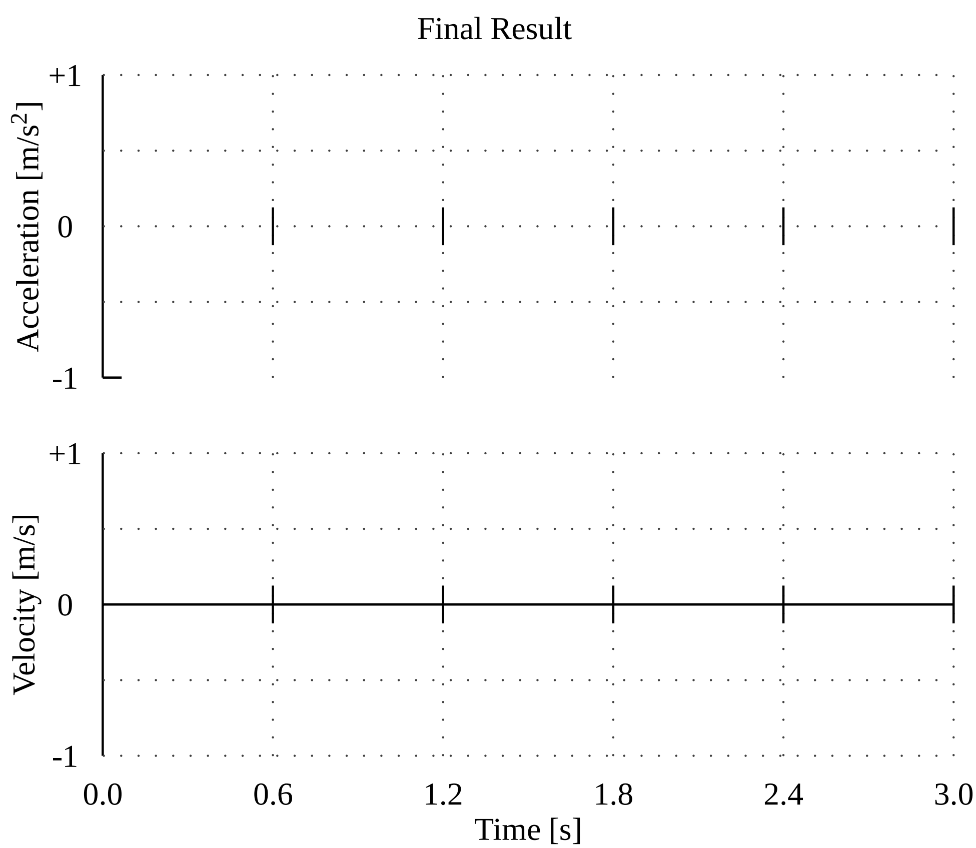
Activity 2.2 Speeding Up Towards the Motion Detector

Suppose now that you start with the cart at the high end of the inclined track, so that it moves towards the motion detector.

1. As the cart *moves toward* the detector and *speeds up*, predict the direction of the acceleration. Will the acceleration be positive or negative based on your general rule from Step 11 from the previous Activity? Sketch your predictions for the velocity-time and acceleration-time graphs on the axes which follow.



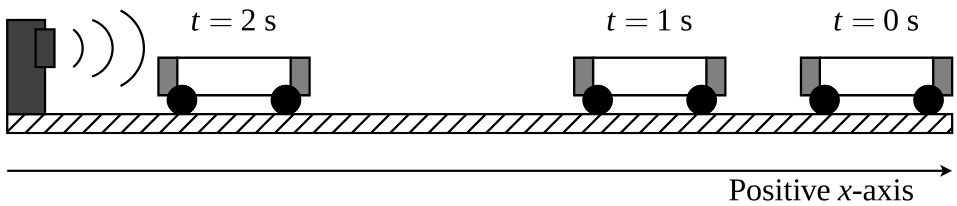
2. Test your predictions. Set up the ramp so that the cart will be *moving towards* the detector and *speeding up*. When you hear the clicks from the motion detector, release the cart from rest from the far end of the ramp. Stop the cart when it reaches the 0.5 meter line. Sketch your graphs on the axes that follow.



3. How does your *velocity-time* graph show that the cart was moving toward the detector?

4. During the time that the cart was speeding up, was the acceleration positive or negative? Does this agree with your prediction? Explain how *speeding up* while *moving toward* the detector results in this sign of acceleration. Hint: look at how the velocity is changing.

5. The diagram below shows the positions of the cart at equal time intervals. At each indicated time, sketch a vector above the cart which might represent the velocity of the cart at that time while it is *moving toward* the motion detector and *speeding up*.



6. Show below how you would find the vector representing the change in velocity between the times 1 s and 2 s in the diagram above. Based on the direction of this vector and the direction of the positive *x*-axis, what is the sign of the acceleration? Does this agree with your general rule from Step 11 in the previous Activity? You need to draw the vectors.

7. Was your general rule in Step 11 of the previous Activity correct? If not, modify it and restate it here.

8. There is one more possible combination of velocity and acceleration for the cart: *moving toward* the detector and *slowing down*. Use your general rule to predict the direction and sign of the acceleration in this case. Explain why the acceleration should have this direction and this sign in terms of the sign of the velocity and how the velocity is changing.

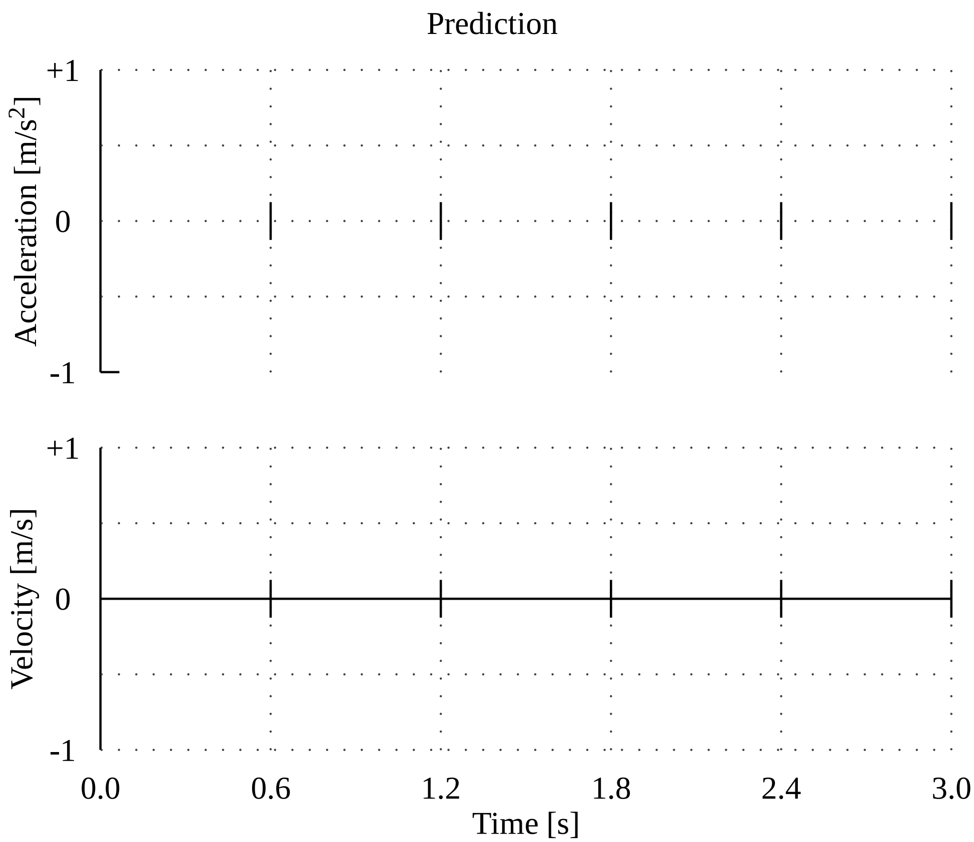
Activity 2.3 Reversing Direction

In this Activity you will look at what happens when the cart slows down, reverses its direction and then speeds up in the opposite direction. How is its velocity changing? What is its acceleration?

1. Set up the ramp so that the motion detector is at the bottom of the incline.

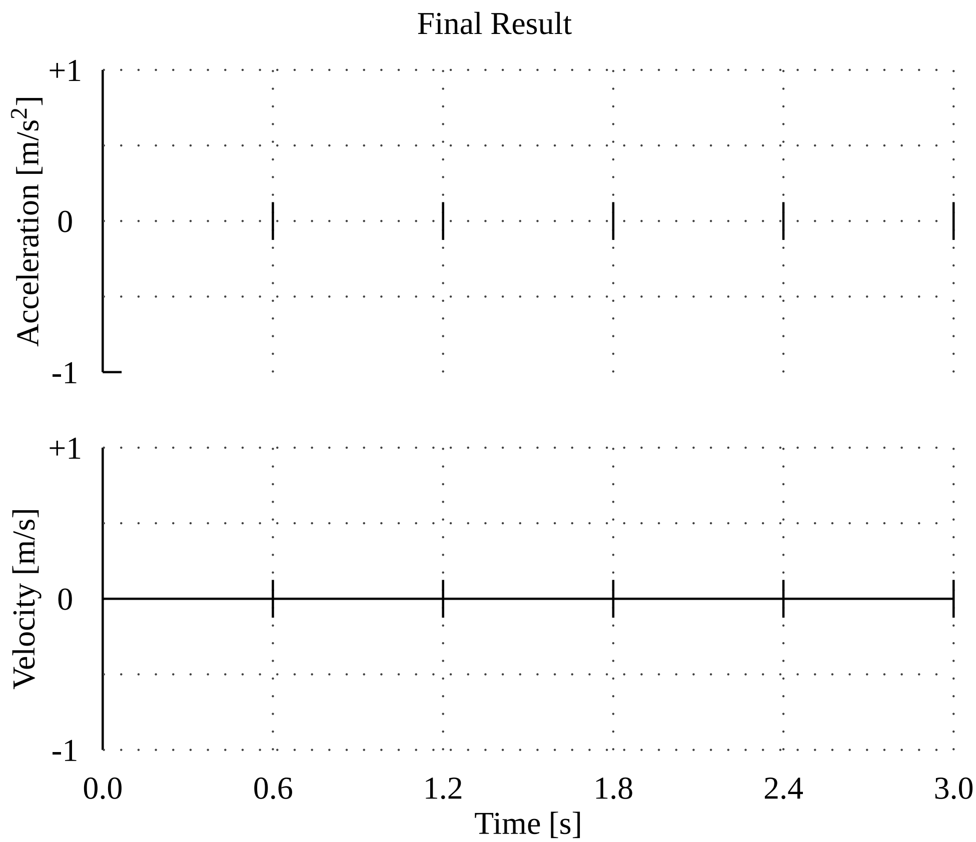
2. Give the cart a push away from the motion detector. It moves away, slows down, reverses direction and then moves back toward the detector. Try it first without using the motion detector. **Be sure to always stop the cart before it hits the motion detector!**

3. Sketch on the axes which follow your predictions of the velocity-time and acceleration-time graphs of this entire motion.



4. Test your predictions. Start with the back of the cart near the 0.5 meter mark. When you begin to hear the clicks from the motion detector, give the cart a gentle push away from the detector so that it travels at least one meter, slows down, and then reverses its direction and moves toward the detector. Be sure to stop the cart by the 0.5 meter line, keep it from hitting the motion detector. You may have to try a few times to get a good round trip. Don't forget to change the scales if this will make your graphs clearer.

5. When you get a good round trip, sketch both graphs on the following axes.



6. Label both graphs with:

    - "A" where the cart started being pushed.
    - "B" where the push ended (where your hand left the cart).
    - "C" where the cart reached its turning point (and was about to reverse direction).
    - "D" where you stopped the cart.

7. Did the cart "stop"? Hint: look at the velocity graph. What was the velocity of the cart at its turning point? Does this agree with your prediction? If it did stop, how much time did it spend at zero velocity before it started back toward the detector? Explain.

8. According to your *acceleration-time* graph, what is the acceleration at the instant the cart reaches its turning point? Is it positive, negative or zero? Is it any different from the acceleration during the rest of the motion? Does this agree with your prediction?

9. Explain the observed sign of the acceleration at the turning point. (Hint: remember that acceleration is the rate of change of velocity. When the cart is at its turning point, what will its velocity be in the next instant? Will it be positive or negative?)

10. On the way back toward the detector, is there any difference between these velocity-time and acceleration-time graphs and the ones which were the result of the cart gliding back from rest (Activity 2.2)? Explain.

11. For each part of the motion—away from the detector, at the turning point and toward the detector, indicate in the table below whether the velocity

is positive, zero or negative. Also indicate whether the acceleration is positive, zero or negative.

	Moving Away	Turning Point	Moving Toward
Velocity			
Acceleration			

12. Imagine that you throw a ball up into the air. It moves upward, reaches its highest point and then moves back down toward your hand. Assuming that upward is the positive direction, indicate in the table that follows whether the velocity is positive, zero or negative during each of the three parts of the motion. Also indicate if the acceleration is positive, zero or negative. Hint: remember that to find the acceleration, you must look at the change in velocity.

	Moving Up (But After Release)	At Highest Point	Moving Down
Velocity			
Acceleration			

13. In what ways is the motion of the ball similar to the motion of the cart which you just observed?

Lab 4

Projectile Motion

Pre-Lab: Projectile Motion

Name:______________________________ Section:______

1. In this lab you will use the *range equation*

$$R = \frac{v_0^2}{g} \sin 2\theta_0$$

to calculate how far a ball will fly when launched from a projectile launcher. Show how to derive the *range equation* starting with the equations of 1-D motion

$$\begin{aligned} x &= x_0 + v_{x0}t \\ y &= y_0 + v_{y0}t - \frac{1}{2}gt^2 \ . \end{aligned}$$

You may use other 1-D motion equations if you wish. Hints:

$$\begin{aligned} v_{x0} &= v_0 \cos\theta_0 \\ v_{y0} &= v_0 \sin\theta_0 \end{aligned}$$

$$2\sin\theta\cos\theta = \sin 2\theta$$

2. Is the *range equation* still appropriate if the ball lands at a different height (y-coordinate) than the one it was launched from?

3. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

4. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Projectile Motion

> We can lick gravity, but sometimes the paperwork is overwhelming.
>
> Wernher von Braun

Objectives

- To explore the nature of motion near the earth's surface
- To describe the gravitational force, which correctly accounts for the falling motion of objects observed near the earth's surface
- To model the motion of an object under the influence of the gravitational force near the earth's surface.

Overview

Initially when asked to define forces most people think of a force as an obvious push or pull such as a punch to the jaw or the tug of a rubber band. By studying the acceleration that results from a force when little friction is present, we came up with a second definition of force as that which causes acceleration. These two alternative definitions of force do not always appear to be the same. Pushing on a wall doesn't seem to cause the wall to move. An object dropped close to the surface of the earth accelerates and yet there is no visible push or pull on it.

The genius of Newton was to recognize that he could define net force or combined force as that which causes acceleration, and that if the obvious applied forces did not account for the degree of acceleration then other "invisible" forces must be present. A prime example of an invisible force is the gravitational force—the attraction of the earth for objects. When an object falls close to the surface of the earth there is no obvious force being applied to it. Whatever is causing it to move is invisible.

Most people rather casually refer to the cause of falling motions as the action of "gravity." What is "gravity"? Can we describe its effects mathematically? Can Newton's Laws be interpreted in such a way that they can be used for the mathematical prediction of motions that are influenced by "gravity"? In this lab you will first study motion and the gravitational force.

Part I Projectile Motion and gravity

At the end of *Changing Motion* you were asked to compare the motion that you studied to that of a ball tossed vertically into the air. If the ball is projected outward and upward we no longer have one dimensional vertical motion. However, the horizontal range can be obtained and is conveniently given by the equation

$$R = \frac{v_0^2}{g} \sin 2\theta_0 \ , \tag{4.1}$$

called the *Range Equation*. By measuring R and θ_0, the range and angle of projection, we can determine the magnitude of the initial velocity, assuming that $g = 9.8$ m/s^2. To carry out your measurements you will need:

- Projectile launcher with plastic ball
- Regular paper and carbon paper
- Meter stick

Activity 1.1 Motion of a Ball Projected at 30 degrees

Safety glasses are required for this part of the experiment.

1. Clamp the projectile launcher to a lab stool.
2. Adjust the angle of the launcher to 30 degrees.

3. Place the plastic ball into the launcher and, using the rod, push it in to the second position.

4. Shoot the ball 10 times and determine the average range by placing the paper and carbon paper on the table top. Make sure that the point where the ball leaves the launcher and the point where it lands on the table are at the same height above the floor (think about why this is important).

Trial	Distance [m]
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average	

5. Determine the magnitude of the initial velocity using the *range equation* given above.

$v_0 =$______

Activity 1.2 Motion of a Ball Projected at 60 degrees

You now have a reasonable estimate for the initial speed of the ball when the spring is compressed to the second position. Now it's time to predict the range for a different angle of elevation.

1. Using the speed of the ball from the previous Activity, predict the range for an angle of 60 degrees using the range equation above.

   $R =$ ______

2. Repeat the procedure from the previous Activity for an angle of 60 degrees and compare the average range to your predicted range.

Trial	Distance [m]
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average	

3. Discuss your results.

Part II More Projectile Motion

Another way to investigate motion is to try to predict how far an object will fall when it is launched horizontally. To do this, you will use a ramp to accelerate a ball onto the table to launch it horizontally. The ball should pass through a photogate and then fall onto a photoplate. These will give you a time from launch until it lands. By changing the height of the ramp where the ball is released, one can change the speed of the ball when it launches. You will need:

- Ramp with ball
- Photogate, photoplate, and timing software
- Meter stick

Activity 2.1 Energy Conservation

1. Open the program *Gate Timer* from the desktop. Find the distance that the ball moves horizontally for several different heights on the ramp. One of your trials should be from the top of the ramp. Record these as well as the time for the fall in the following table:

Height Above the Table [m]	Horizontal Distance [m]	Time for Fall [s]

2. Is there a way that you can predict how far the ball will go (the horizontal distance) when launched from a certain height? If so how? (Hint: Use *Conservation of Energy*. What are the two types of energy we are looking at?)

3. Now predict the distance the ball will travel, using the equation you just calculated, for the height at the top of the ramp, as well as a height of 50 meters (assume the same time for fall).

4. Now compare your prediction for the top of the ramp to the experiment. You will notice the calculation overestimates the value by 30-40%. What is the reason for this difference?

5. Why does the time not change significantly even thought the velocity does vary?

Part III Projectile Motion in Two Dimensions

The range equation that you used in the first part of the lab is useful, but it is not particularly instructive in understanding the true nature of the motion. If we think of the ball as a particle, then a much better approach would be to set up an *x*-*y* coordinate system and map the position of the particle at each instant of time so that we can determine the *x* and *y* displacements as a function of time.

For 1-dimensional motion we have used a motion detector to do this for us. For 2-dimensional motion we can digitize a video of the motion and do a similar analysis. However, we should realize that a projectile motion analysis applies not just to particles but also to collections of particles if we track the motion of the *Center of Mass* (that point of a body where all the mass can be considered to be concentrated). You will need:

- Movie analysis software
- Spreadsheet program (*Excel*)

Activity 3.1 2-D Projectile Motion

In this activity we will use video analysis software and a spreadsheet to model our "projectile motion".

1. At your computer stations, go to the desktop and open the file *granjete*. At the next prompt, tell it you want 1 point per screen.

2. Maximize the movie by clicking on *Movie* on the *Menu Bar* and then again on *Double Size*. You now want to click on the *Ruler Icon* on the *Left Menu Bar* so that you can calibrate the image. Click on *continue* and then click on the left and right ends of the *calibration scale* at the bottom of the field of view.

3. At the bottom of the video screen is a *Play Button* (Left Side) and *Single Advance Buttons* (Right Side). Click on these and see what happens.

4. This video had 30 frames per second. If you move your pointer across the video screen you should see a bulls eye and this will be used to locate the position of your estimate of the center of mass of the ballerina. Advance your video to the second frame and click on your estimate for the position of the center of mass. Continue to do this frame-by-frame. As you do this, a data table is being generated which you can see after you are done by clicking on the *Table Icon* on the *Left Menu Bar*.

5. Now click and drag on the data table until the entire table is shaded. Move your pointer to the top *Menu Bar*, click on *Edit* and *Copy Data*. Click on the *Minimize Button* in the upper right corner of the screen. Open the *granjete excel* spreadsheet, located on the computer desktop. In *Excel* , click on the *Edit* menu and select *Paste*. Your data table should appear in your spreadsheet in the t, x, and y columns.

6. You now have three columns of data which give you time, and the corresponding values for x and y.

7. There should be 2 graphs displayed on the right side of the spreadsheet:

   - x vs. t
   - y vs. t

   Each graph will have a pink line and a purple line on it. The purple line represents ballerina's position data that was recently pasted into the spreadsheet. The pink line represents a numerical model, which is created based on the initial position, velocity and acceleration parameters input in the top right of the spreadsheet. Currently, the initial position, velocity and acceleration in the x and y direction is set to one. Play around with the numbers (keeping in mind how physics must work) for each category to try to get the model to match the ballerina's graph.

8. Can you determine the angle that the ballerina's initial velocity made with the horizontal? Based on what you have learned about the range equation, why would it be good for a ballerina to jump at that angle?

Lab 5

Force And Motion

Pre-Lab: Force and Motion

Name:______________________________ Section:______

1. What is Newton's Second Law?

2. Give a real-life example that demonstrates Newton's Second Law.

3. Suppose that you're asked to design a race car. If you want to maximize the acceleration, should you design the car to be as massive as possible, or as lightweight as possible (assume the engine provides the same amount of force in both cases)? Why?

4. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

5. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Force And Motion

A vulgar Mechanik can practice what he has been taught or seen done, but if he is in an error he knows not how to find it out and correct it, and if you put him out of his road, he is at a stand; whereas he that is able to reason nimbly and judiciously about figure, force and motion, is never at rest til he gets over every rub.

Isaac Newton

Objectives

- To learn how to use a force probe to measure force.
- To understand the relationship between force applied to an object and its motion.
- To find a mathematical relationship between the force applied to an object and its acceleration.

Overview

In the previous labs, you have used a motion detector to display position-time, velocity-time and acceleration-time graphs of the motion of different objects. You were not concerned about how you got the objects to move, i.e. what *forces* (pushes or pulls) acted on the objects. From your experiences, you know that force and motion are related in some way. To start your bicycle moving, you must apply a force to the pedal. To start up your car, you must step on the gas pedal to get the engine to apply a force to the road through the tires.

But exactly how is force related to the quantities you used in the previous unit to describe motion—position, velocity and acceleration? In this unit you will pay attention to forces and how they affect motion. You will first develop an operational idea of a force as a push or a pull. You will learn how to measure forces. Then you will apply forces to a cart, and observe the nature of its resulting motion graphically with a motion detector.

Part I Motion and Force

You can now use the force probe to apply measured amounts of force to an object. You can also use the motion detector to examine the motion of the object. In this way you will be able to establish the relationship between motion and force.

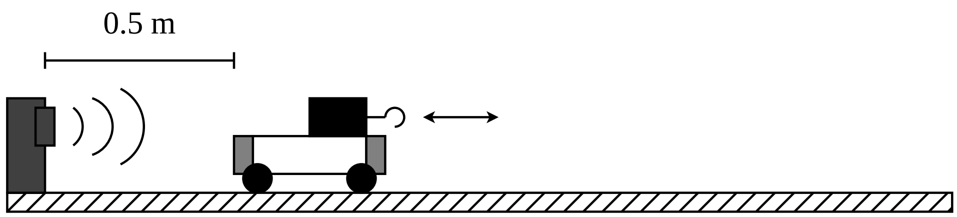
You will need the following materials:

- Computer
- Force probe
- Motion detector
- Cart
- Smooth ramp or other level surface 2-3 meters long
- Low friction pulley
- String
- Variety of masses

Activity 1.1 Pushing and Pulling a Cart

In this activity you will move a cart by pushing and pulling it with your hand. You will measure the force, velocity and acceleration. Then you will be able to look for relationships between the applied force and the motion quantities, to see which is (are) related to force.

1. Set up the cart, force probe and motion detector on a smooth level surface as shown below. The cart should have a mass of about 700 g with force probe included. Fasten additional mass to the top if necessary.



   The force probe should be fastened securely to the cart. Plug the force probe into *channel 2*. The motion detector should be plugged into *dig/sonic 2*. Make sure the cable from the force probe will not be seen by the motion detector.

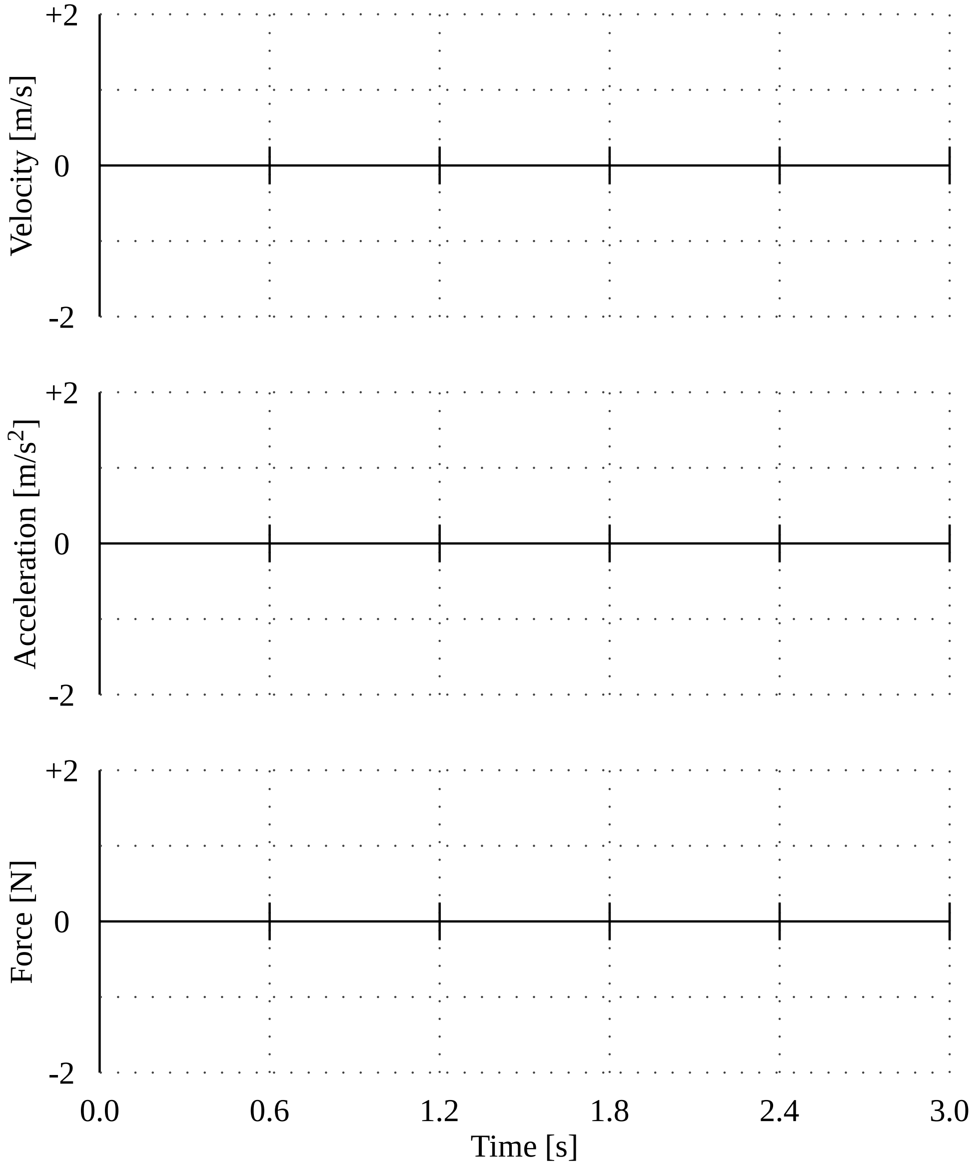
2. Suppose you grasp the force probe hook and move the cart forwards and backwards in front of the motion detector. Do you think that either the velocity or the acceleration graph will look like the force graph? Which of these motion quantities is most directly related to force? Explain.

3. To test your predictions, open the experiment file called *Force_and_Motion-_A1-1.exp* (*Motion and Force*). This will set up velocity, force and acceleration axes with a convenient time scale of 5 s, as shown below. Calibrate

the force probe by clicking on *Experiment* on the *Menu* bar and choose *Calibrate*. Choose the *Force icon* (channel 2) and click *Perform Now*. Enter in 0 for the first value, and click *keep*. Calibrate the probe in Newtons by hanging a 500 gram mass from it, which works out to 5.39 N including the 50 g hanger. Click *keep*, and then click *OK*.

4. Grasp the force probe hook and click *Start*. When you hear the clicks, pull the cart away from the motion detector, and quickly stop it. Then push it back towards the motion detector, and again quickly stop it. Pull and push the force probe hook along a straight line—do not twist it. Be sure that the cart never gets closer than 0.5 m from the detector.

5. Carefully sketch your graphs on the axes below, or print them and affix the graphs over the axes.

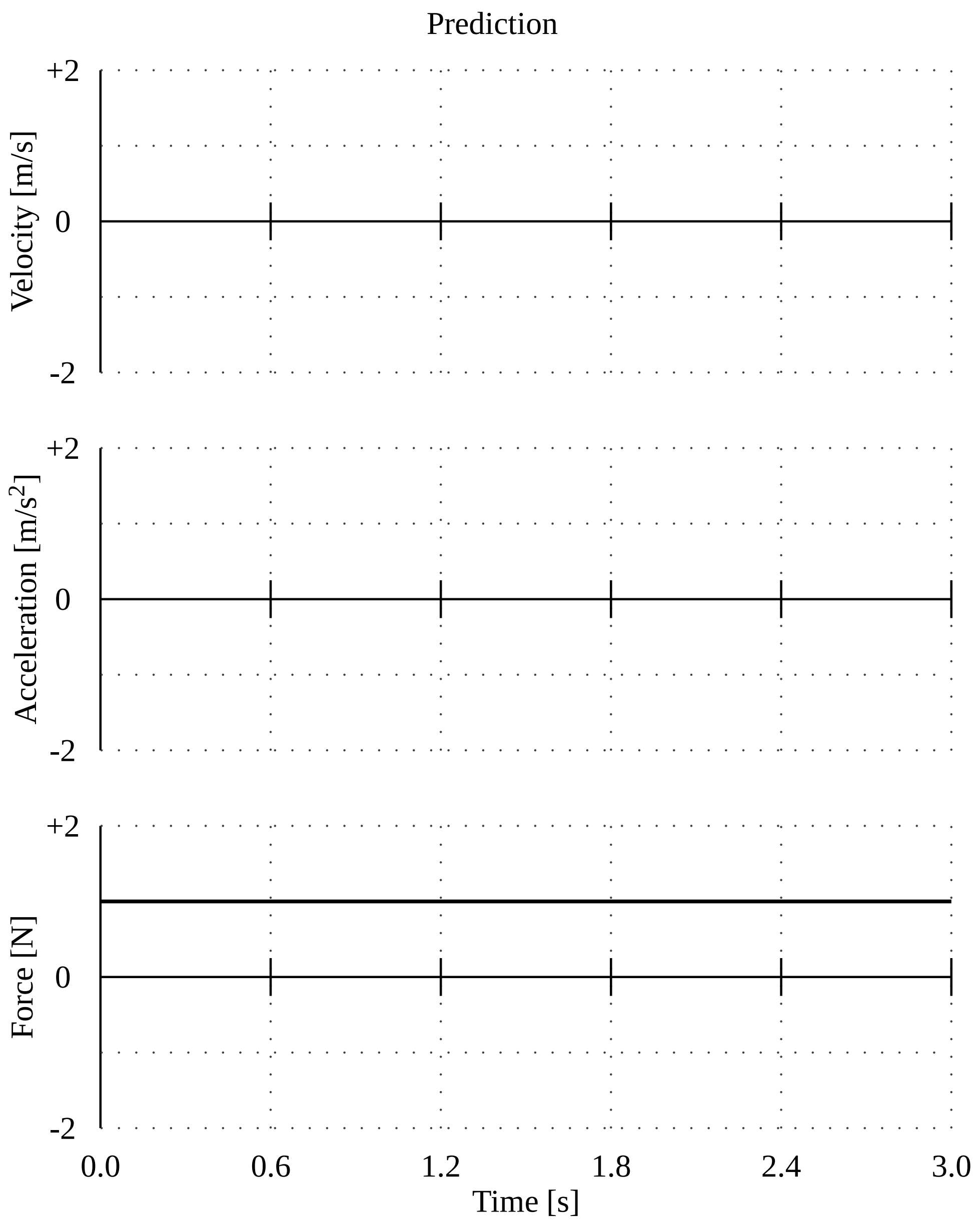


6. Does either graph—velocity or acceleration—resemble the force graph? Which is most directly related to the applied force? Why?

Activity 1.2 Speeding Up

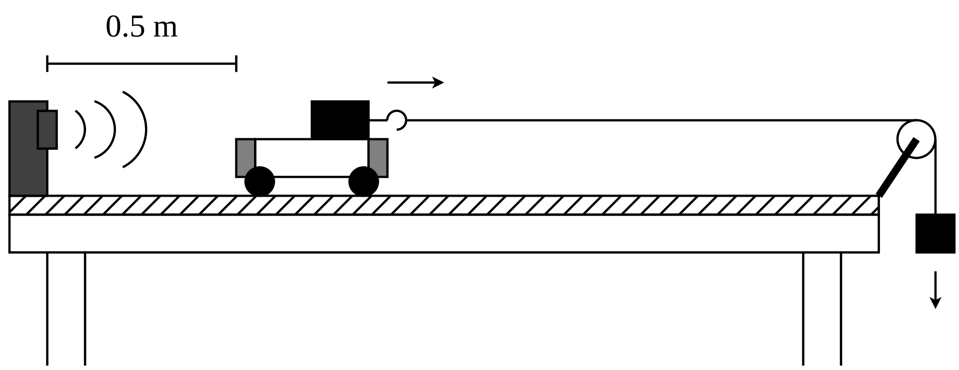
You have seen in the previous activity that force and acceleration seem to be related. But just what is the relationship between force and acceleration?

1. Suppose you have a cart with very little friction, and that you pull this cart with a constant force as shown below on the force-time graph. Sketch on the axes below your predictions of the velocity-time and acceleration-time graphs of the cart's motion.



2. Describe in words the predicted shape of the velocity-time and acceleration-time graphs which you sketched.

3. Test your predictions. Set up the ramp, pulley, cart, string, motion detector and force probe as shown below. The cart should be the same mass as before (about 700 g).

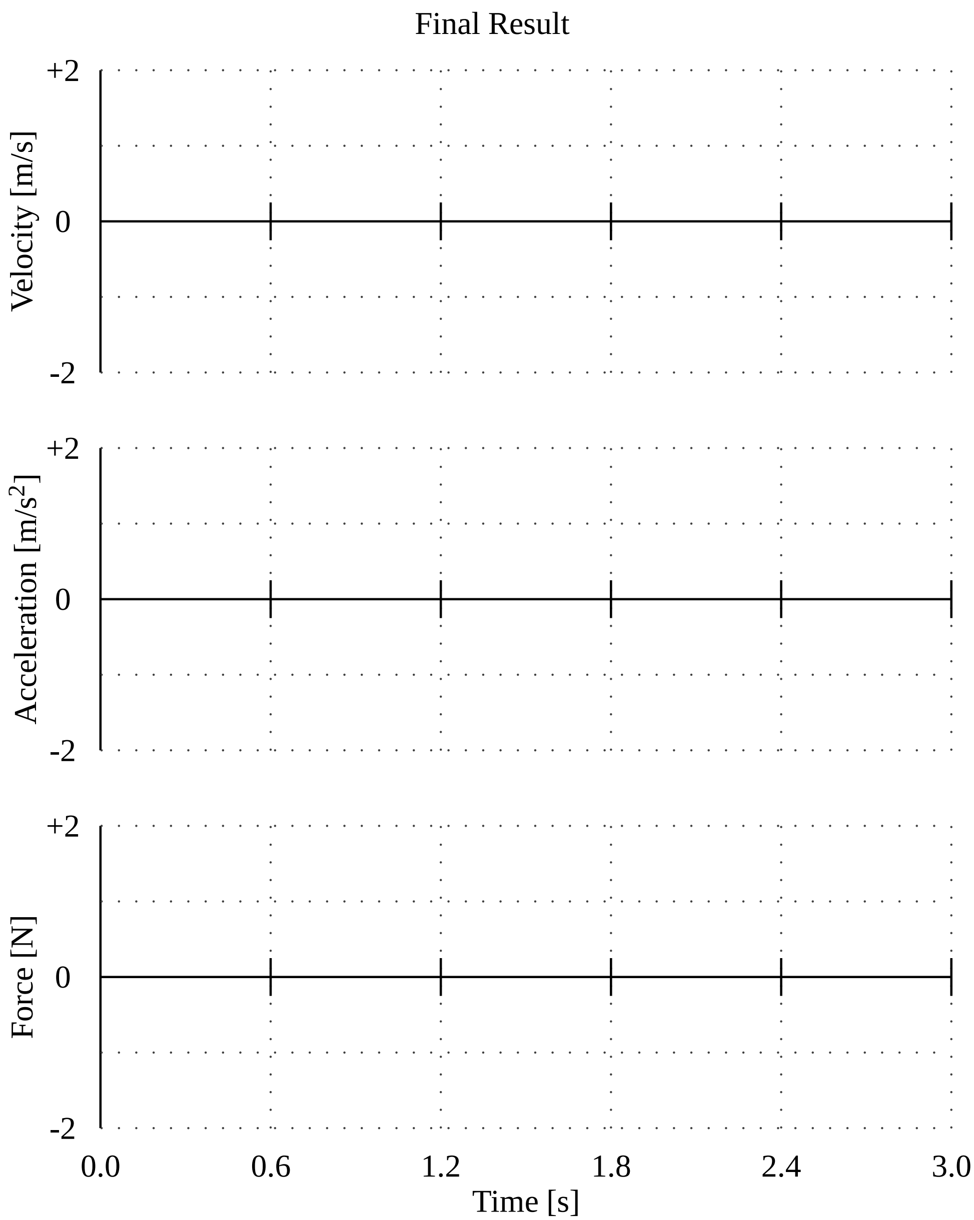


It is important to choose the amount of the falling mass so the cart doesn't move so fast that you can't observe the motion. You should be able to get good results with 50 grams. Also test to be sure that the motion detector sees the cart during its complete motion. **Remember that the back of the cart must always be at least 0.5 meters from the motion detector.**

Record the hanging mass that you decided to use:______g

4. Start graphing. Release the cart after you hear the clicks of the motion detector. **Be sure that the cable from the force probe is not seen by the motion detector, and that it doesn't drag the cart.** Repeat until you get good graphs in which the cart is seen by the motion detector over its whole motion.

5. If necessary, adjust the axes to display the graphs more clearly. Sketch the actual velocity, acceleration and force graphs on the axes below. Draw smooth graphs; don't worry about small bumps.



6. Measure the average force and average acceleration for the cart, and **record your measured values as *Trial 1* in the table at the end of the next activity**. Find the mean values only during the time intervals when the force and acceleration are nearly constant. Click with the cursor on the force graph at the beginning of the time interval over which you want to find the mean force, and—while holding down the mouse button—slide the cursor

across to the end of the interval. This selected region on the graph should darken. Release the mouse, and then select *Statistics*. . . from the *Analysis* menu. The mean value of force will be displayed. Repeat for the mean acceleration.

7. After the cart is moving, is the force which is applied to the cart by the string constant, increasing or decreasing? Explain based on your graph.

8. How does the acceleration graph vary in time? Does this agree with your prediction? What kind of acceleration corresponds to a constant applied force?

9. How does the velocity graph vary in time? Does this agree with your prediction? What kind of velocity corresponds to a constant applied force?

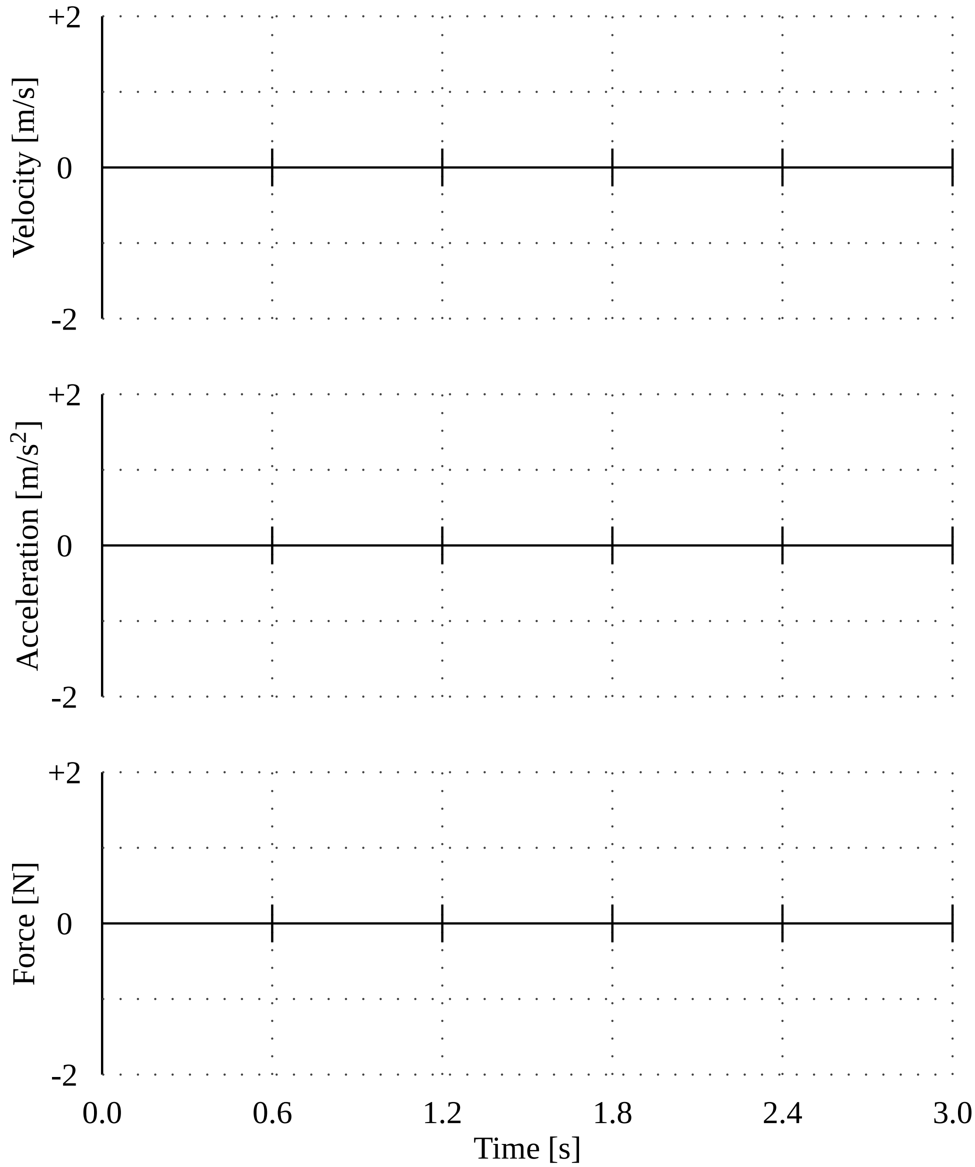
Activity 1.3 Acceleration from Different Forces

In the previous activity you have examined the motion of a cart with a constant force applied to it. But what is the relationship between acceleration and force? If you apply a larger force to the same cart (same mass as before) how will the acceleration change? In this activity you will try to answer these questions by applying different forces to the cart, and measuring the corresponding accelerations. If you accelerate the same cart (same mass) with two other forces, you will then have three data points—enough data to plot a graph of acceleration vs. force. You can then find the mathematical relationship between acceleration and force.

1. Suppose you pulled the cart with forces about three times as large as before. What do you think would happen to the acceleration of the cart? Explain.

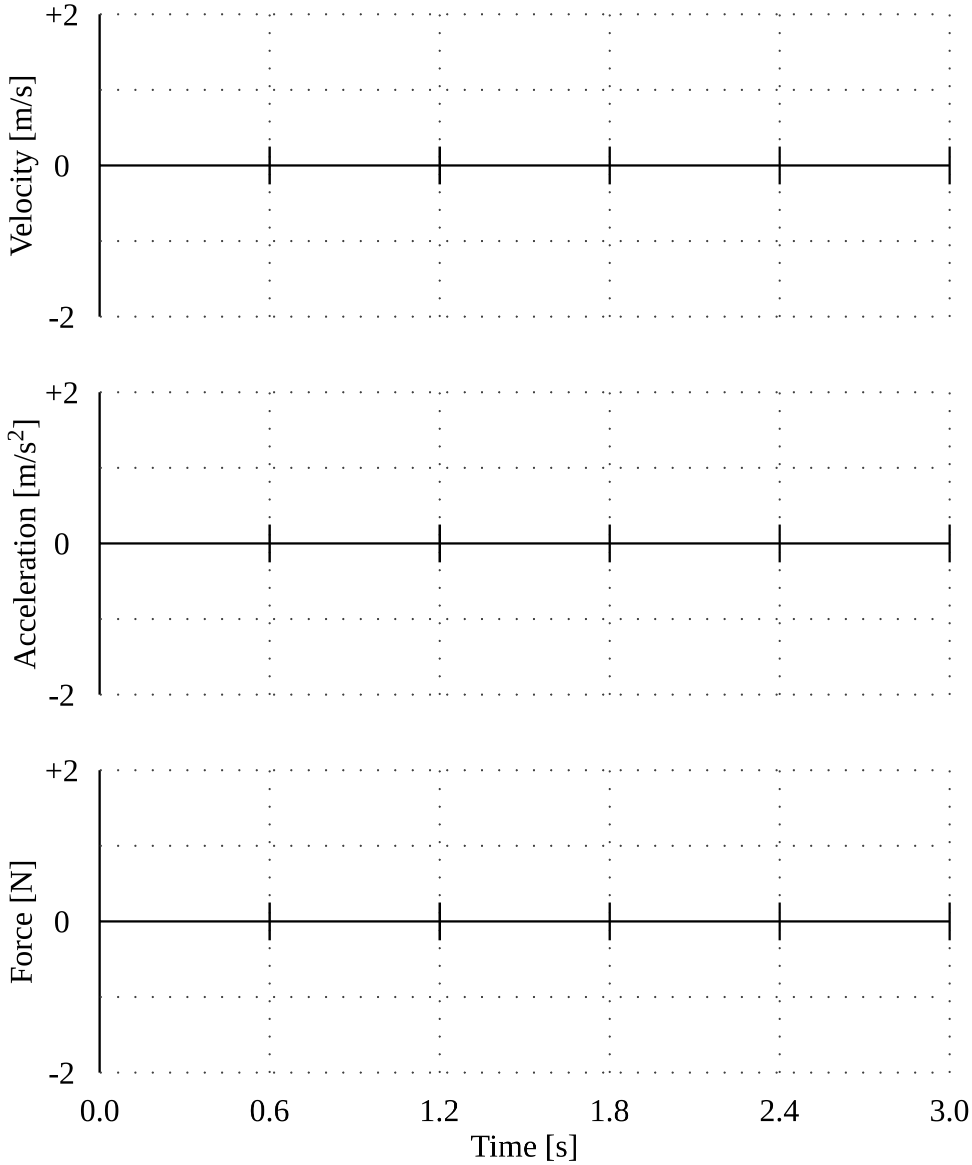
2. Test your prediction. Accelerate the cart with a larger force than before. To produce a larger force, hang a mass about two times as large as in the previous activity (If you used 50 g before, now use 100 g). Record the hanging mass:______g

3. Graph force, velocity and acceleration as before. Sketch your graphs below.



4. Repeat for a hanging mass that is three times larger. Record the hanging mass:______g

5. Graph force, velocity and acceleration as before. Sketch your graphs below.



6. Record your average values in the data table below as *Trial 2* and *Trial 3*.

	Average Force [N]	Average Acceleration [m/s^2]
Trial 1		
Trial 2		
Trial 3		

7. How did the largest force applied to the cart compare to the smallest force?

8. How did the corresponding acceleration of the cart compare to that caused by the smaller force? Did this agree with your prediction? Explain.

Activity 1.4 The Relationship Between Acceleration and Force

In this activity you will find the mathematical relationship between acceleration and force.

1. Close the data acquisition application. You may plot the data by opening *Excel*. Enter the data into the spreadsheet and plot a graph of acceleration as a function of force from the data in the table.

2. Determine the mathematical relationship between the acceleration of the cart and the force applied to the cart as displayed on your graph.

3. Write down the equation from *Excel*, and leave the graph on screen to show your instructor.

4. Does there appear to be a simple mathematical relationship between the acceleration of a cart (with fixed mass) and the force applied to the cart (measured by the force probe mounted on the cart)? What determines the numerical constants in your equation (e.g. the slope and y-intercept)?

Comment:

The relationship which you have been examining between the acceleration of the cart and the applied force is known as *Newton's Second Law*.

5. If you increased the force applied to the cart by a factor of ten, how would you expect the acceleration to change? How would you expect the *acceleration-time* graph of the cart's motion to change? Explain based on your graphs.

6. If you increased the force applied to the cart by a factor of ten, how would you expect the *velocity-time* graph of the cart's motion to change? Explain based on your graphs.

Lab 6

Passive Forces and Newton's Laws

Pre-Lab: Passive Forces and Newton's Laws

Name:______________________________ Section:______

1. What is the difference between *passive* and *active* forces? Give two examples of each.

2. While moving to a new apartment, a physics TA needs to slide a heavy cardboard box along the ground. The box is short and wide (i.e. the top and bottom have large surface areas, and the sides have small surface areas). Can the TA reduce the amount of friction between the box and the ground by tipping the box onto its side? Should they push or pull?

3. If you apply a force to the end of a rope tied to a crate, is the whole force transmitted to the crate, or is the force at the crate smaller or larger than your pull?

4. Suppose that instead of a rope, you use a bungee cord or large rubber band. Will the force applied to the crate be larger, smaller or the same as with the rope?

5. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

6. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Passive Forces and Newton's Laws

> The gem cannot be polished without friction, nor man perfected without trials.
>
> Chinese Proverb

Objectives

- To explore how the presence of friction forces is incorporated into Newton's First and Second Laws of Motion.
- To explore the interaction forces between objects and Newton's Third Law of Motion.
- To explore tension forces and their mechanism.
- To apply Newton's Laws of Motion to a situation with tension included.

Overview

By noting that the motion of falling objects near the surface of the earth is with a constant acceleration, you have concluded, according to *Newton's Second Law*, that there must be a constant (gravitational) force acting on the object.

Finding forces is often hard because some of them are not *active* forces. Rather, they are *passive* forces such as the normal force. (In the case of normal force, the *active* forces are the push you exert on a wall or the gravitational pull on a book sitting on a table.)

Friction and tension forces are other examples of passive forces. The passive nature of friction is obvious when you think of an object like a block being pulled along a rough surface. There is an applied force (active) in one direction and a friction force in the other direction which opposes the motion. If the applied force is discontinued the block will slow down to rest but it will not start moving in the opposite direction due to friction. This is because the friction force is passive and stops acting as soon as the block comes to rest. Likewise, tension forces, such as those exerted by a rope pulling on an object can only exist when there is an active force pulling on the other end of the rope.

In this lab you will use Newton's Laws of Motion to explain friction and tension forces. Along the way you will examine the Third of Newton's Laws of Motion.

Part I Newton's Laws when Friction is Present

In previous labs we have been trying hard to ignore the effects of friction and we have been concentrating on applied forces involving pushes and pulls that we can see and measure directly. The time has come to take friction into account. You can make observations by applying a force directly to your force probe mounted on a cart and comparing its acceleration when no friction is present to that when the friction pad is allowed to drag on the track.

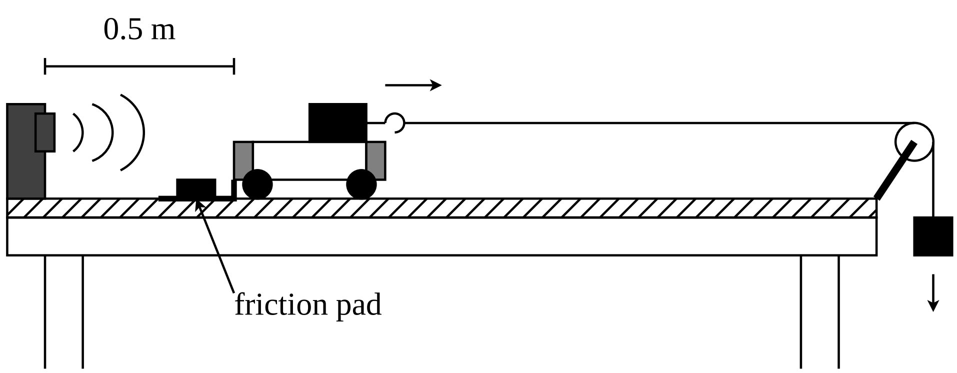
In order to make observations on the effects of friction you will need the following equipment:

- Computer
- Force probe
- Motion detector
- Cart with friction pad
- Smooth ramp or other level surface 2–3 m long
- 50 and 200 gram hanging masses

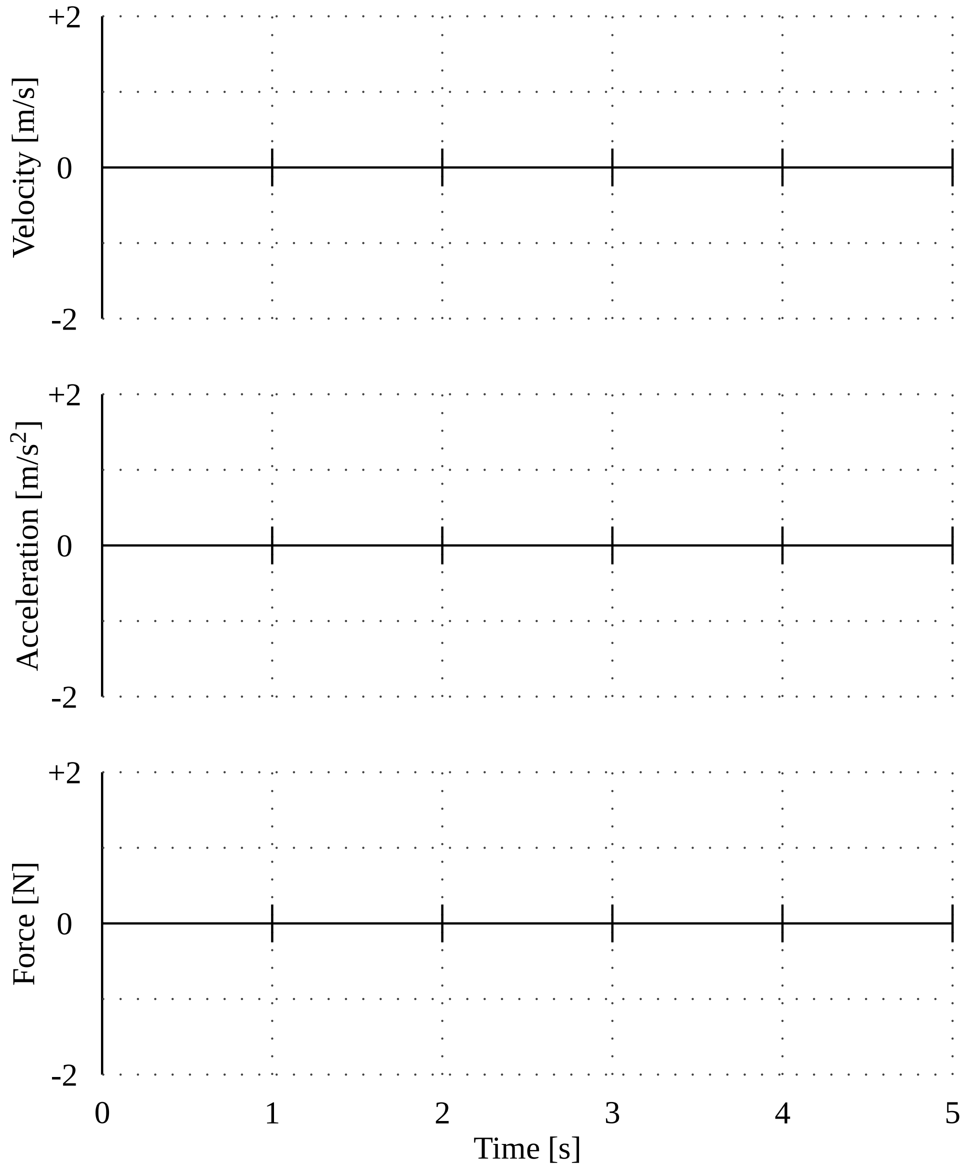
- String

Activity 1.1 The Action of Friction

1. Set up the ramp, motion detector, force probe, cart and falling mass attached to the cart by means of a pulley and string, as shown below.



2. Open the experiment *Passive_Forces_A1-1.exp* (*Action of Friction*) to display the following axes.



3. The force probe should be calibrated with a force of about 5.39 N using a 500 g hanging mass, and including the 50 g weight hanger.

4. Accelerate the cart with a hanging mass of 50 g. Sketch your graphs on the axes.

5. Determine the average applied force and average acceleration of the cart. (Use the mouse to select the time interval when the cart had a constant

acceleration. Select *Statistics* from the *Analysis* menu.) Record your measured values in the spaces below.

Average applied force = _______ N

Average acceleration = _______ m/s^2

6. Add weight to the pad on the cart until it is rubbing against the track just enough to cause it to move at a constant velocity as the 50 g mass falls. Graph the motion of the cart as before. Give the cart a little push to get it started. Sketch your graphs on the same axes above with dashed lines.

7. Find the average acceleration and the average force applied by the string on the cart, and record the values in the spaces below.

   Average force applied to cart = _______ N

   Average acceleration = _______ m/s^2

8. If the cart can move at constant velocity with a force applied to it by the string, is Newton's First Law violated? What should the combined (net) force on the cart be in this case if Newton's First Law is correct?

9. If Newton's First Law correctly describes the motion of the cart at a constant velocity, describe the friction force which must be combined with the force applied by the string. Does this friction force act in the same direction or the opposite direction as the force applied by the string? What is its magnitude? Explain.

10. Suppose that the cart moves with a larger constant velocity. Will the friction force be different from before? Explain.

11. Remove some of the weight from the friction pad a little bit so that it rubs the track lighter than before, and again graph as you accelerate the cart with the 50 g mass falling. Record the average force applied to the cart by the string and the average acceleration of the cart in the spaces below.

    Average force applied to cart = _______ N

    Average acceleration = _______ m/s^2

12. You should have noted that the acceleration of the cart is noticeably less than that which you observed in Step 4 (when the friction pad was not in contact with the ramp). Is Newton's Second Law violated? Can you state a friction force as in Step 9 to combine with the force applied by the string so that Newton's Second Law ($F_{net} = ma$) correctly describes the motion? Explain.

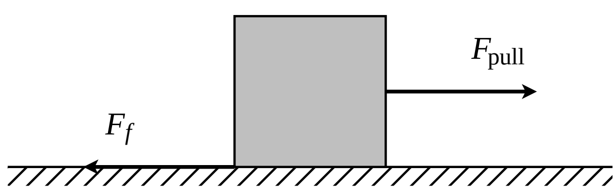
13. Based on the measured acceleration and the mass of the cart, what should the magnitude of the combined (net) force on the cart be if Newton's Second Law is correct? Calculate the magnitude and direction of the new friction force caused by the dragging pad if Newton's Second Law is correct.

Part II Passive Forces and Newton's Laws

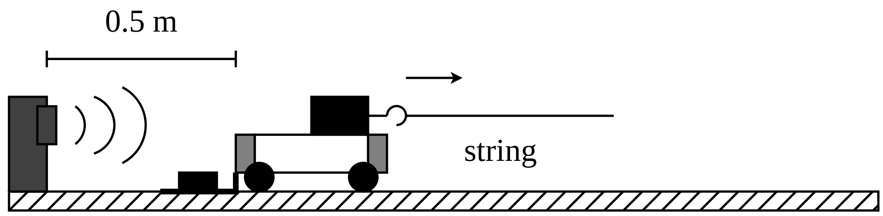
Activity 2.1 Friction and Normal Forces

You have seen in Activity 1.1 that when the surface of the friction pad is in contact with the surface of the track, the track exerts a friction force on the pad. If the friction force is equal in magnitude to the applied force, then the cart either remains at rest or moves with a constant velocity. Friction forces when two objects are sliding along each other are called *kinetic* friction forces. If the objects are not sliding along each other, then the friction forces are called *static* friction forces. In this investigation you will examine whether the friction force is different when an object is at rest (*static* friction) than when it is sliding along a track (*kinetic* friction).

1. Consider a block sitting on a table, as shown below. You pull on a string attached to the block, and the block doesn't move because the friction force opposes your pull. You pull harder, and eventually the block begins to slide along the table top. Predict how the friction force just before the block started sliding compares to the force when the block is actually sliding? Explain.

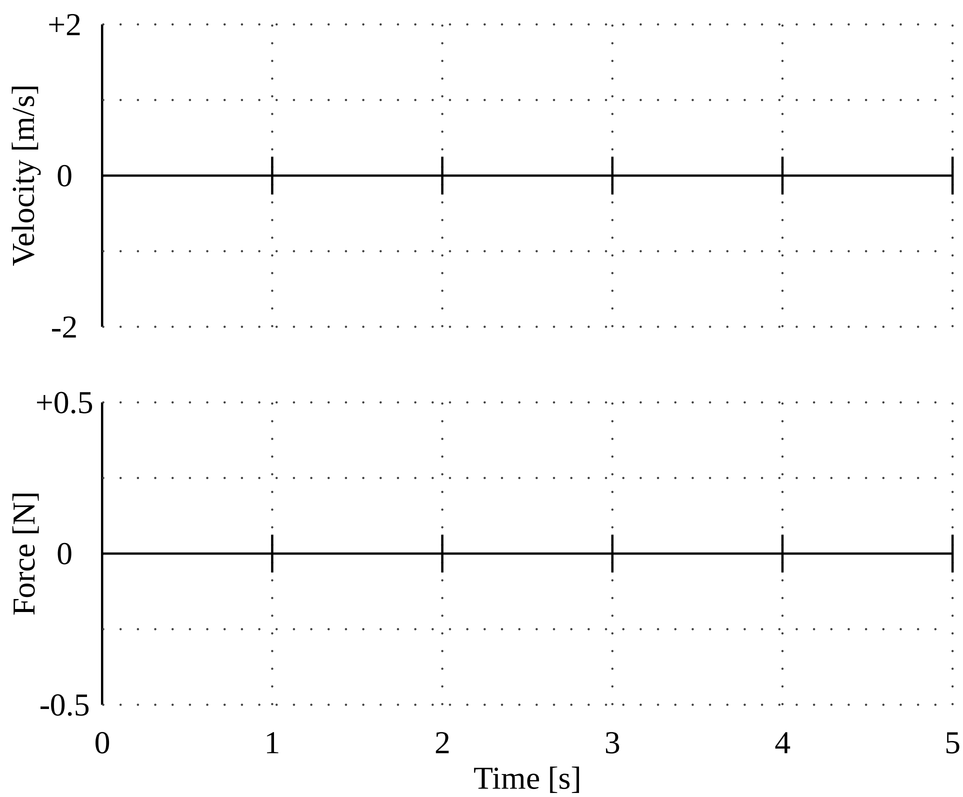


2. Set up the cart with friction pad, string, force probe, motion detector and ramp as shown below. The force probe is already attached to the cart.



3. Measure the mass of the cart and force probe: ______kg

4. Open the experiment *Passive_Forces_A2-1.exp* (*Static and Kinetic Friction Force*) to display the axes shown below.



5. Start graphing with the string loose, then gradually pull **very gently** on the force probe with the string, and increase the force very slowly. Be sure that you pull horizontally—not at an angle up or down. When the cart begins to move, pull only hard enough to keep it moving with a small velocity which is as constant (steady) as possible.

6. Sketch your graphs using solid lines on the axes above.

7. Mark an arrow on your force graph at the time when the cart just began to move. How do you know when this time is?

8. What happens to the friction force *just* as the cart begins to move? Does this agree with your prediction? Is there a difference in magnitude between the *static friction* force just before an object begins to slide and the *kinetic friction* force when it is sliding?

Part III Tension Forces

When you pull on a rope attached to a crate, your pull is somehow transmitted down the rope to the crate. *Tension* is the name given to forces transmitted in this way along strings, ropes, rubber bands, springs and wires.

Is the whole force you apply transmitted to the crate, or is the pull at the other end larger or smaller? Does it matter how long the rope is? How is the force "magically" transmitted along the rope? These are some of the questions you will examine in this investigation.

Obviously the rope by itself is unable to exert a force on the crate if you are not pulling on the other end. Thus, tension forces are passive just like friction and normal forces. They only act in response to an active force like your pull.

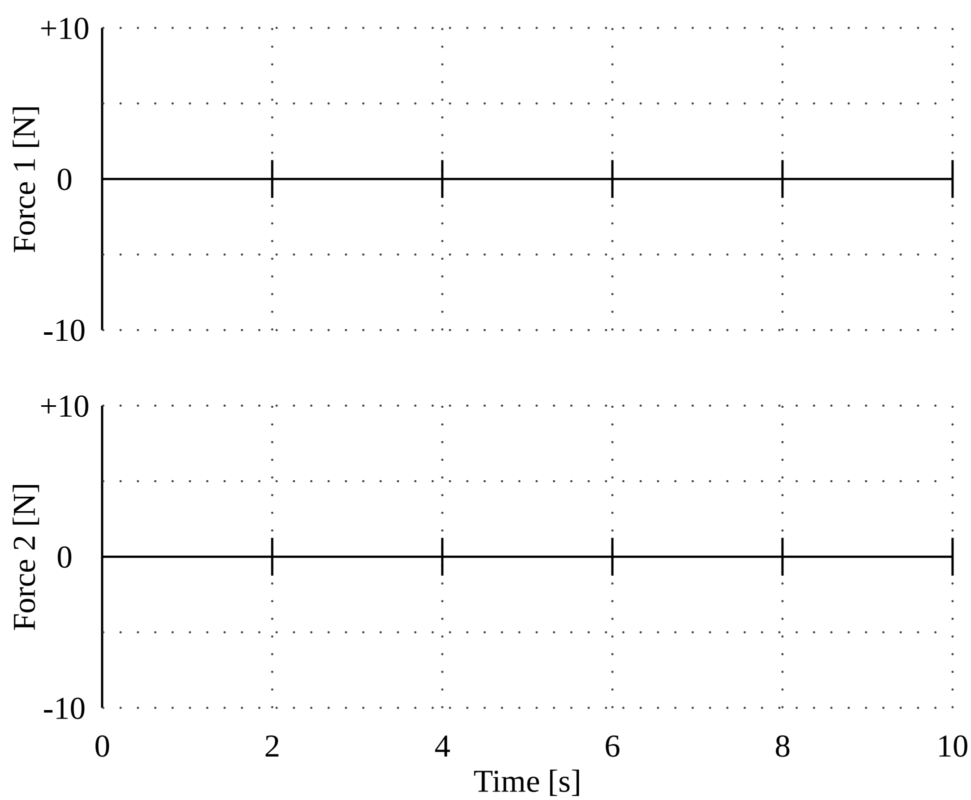
To test your predictions you will need the following:

- Two force probes

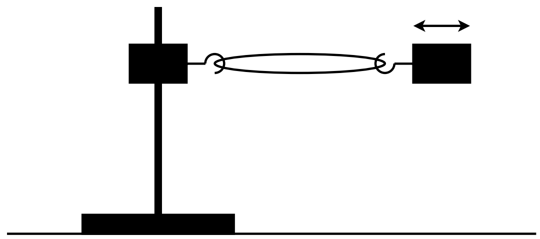
- Computer
- Masses to calibrate the force probes
- A rubber band
- A piece of string

Activity 3.1 Mechanism of Tension Forces

1. Connect the force probes to the ports labeled *ch 2* and *ch 3*. Open the experiment *Passive_Forces*_A3-1.exp (*Tension Forces*) to display the axes shown below.



2. Calibrate both force probes with 500 g masses as before.
3. Attach force probe 1 horizontally to a stable stand such as a heavy ring stand so that it won't move when pulled.



4. Place a rubber band between the force probes.

5. Start graphing, pull softly at first on force probe 2 and then harder, then vary the applied force up and down. **Be sure not to exceed 5 N**.

6. Sketch the graphs on the axes above.

7. Based on the readings of the two force probes, when you pull on one end of the rubber band, is the force transmitted down to the other end? Explain.

8. As you increase the force applied to the rubber band, what happens to the length of the rubber band? Propose a mechanism based on these observations to explain how the force is transmitted down the rubber band from force probe 2 to force probe 1.

9. Indicate with arrows on the diagram on the previous page the directions of the forces exerted by the rubber band on force probe 1 and force probe 2.

10. Make loops at both ends of the short piece of string, and replace the rubber band with it. Repeat Step 5.

11. Based on the readings of the two force probes, when you pull on one end of the string, is the force transmitted undiminished down to the other end? Does it matter how long the string is? Explain.

12. Did the string stretch at all when you pulled on it? Can you propose a mechanism for the transmission of the force along the string?

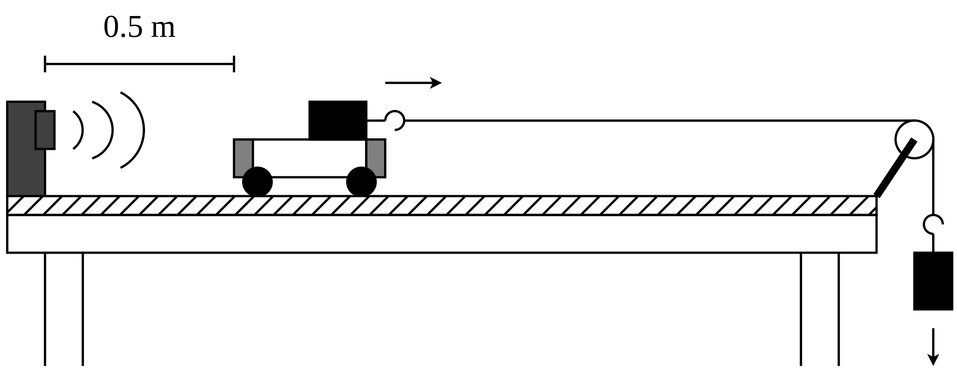
Activity 3.2 Tension When a String Changes Direction

What happens when a string is hung around a pulley? Is the tension force still transmitted fully from one end of the string to the other?

In addition to the equipment listed above you will need:

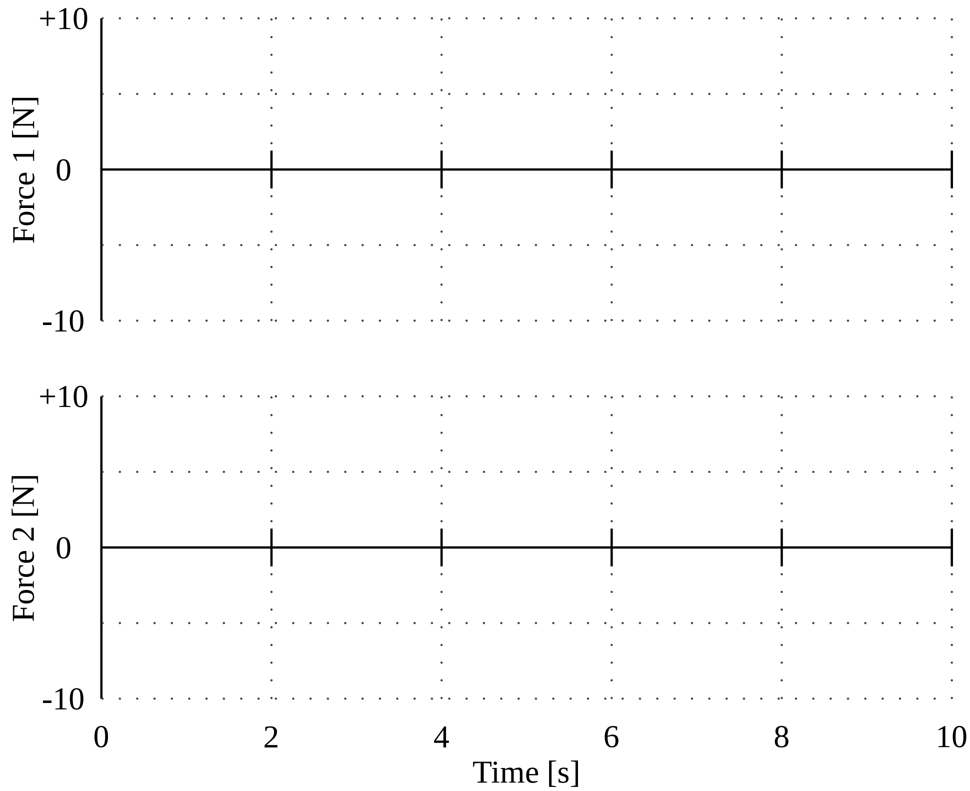
- Low-friction pulley
- Cart
- Smooth level track 2-3 m in length
- 200 and 500 gram masses
- Computer
- Motion detector

1. Attach force probe 1 securely to the cart, and set up the cart, track, pulley, string and force probe 2.



2. Start graphing while pulling on force probe 2 and holding the cart to keep it from moving. Pull gently at first, then pull harder and alternate soft and hard. Do not exceed 5 N.

3. Sketch your graphs on the following axes.



1. Based on your observations of the readings of the two force probes, was the pull you exerted on force probe 2 transmitted undiminished to force probe 1 even though it went through a right angle bend? Is this what you expected? Explain.

2. Now suppose that in place of force probe 2 you hang a 100 g mass from the end of the string. With the cart at rest, what value do you expect force probe 1 to read? Be specific.

3. Suppose that you hang the same 100 g mass but release the cart and let it accelerate as the mass falls. Do you expect force probe 1 to read the same force or a larger or smaller force as the cart accelerates? Explain.

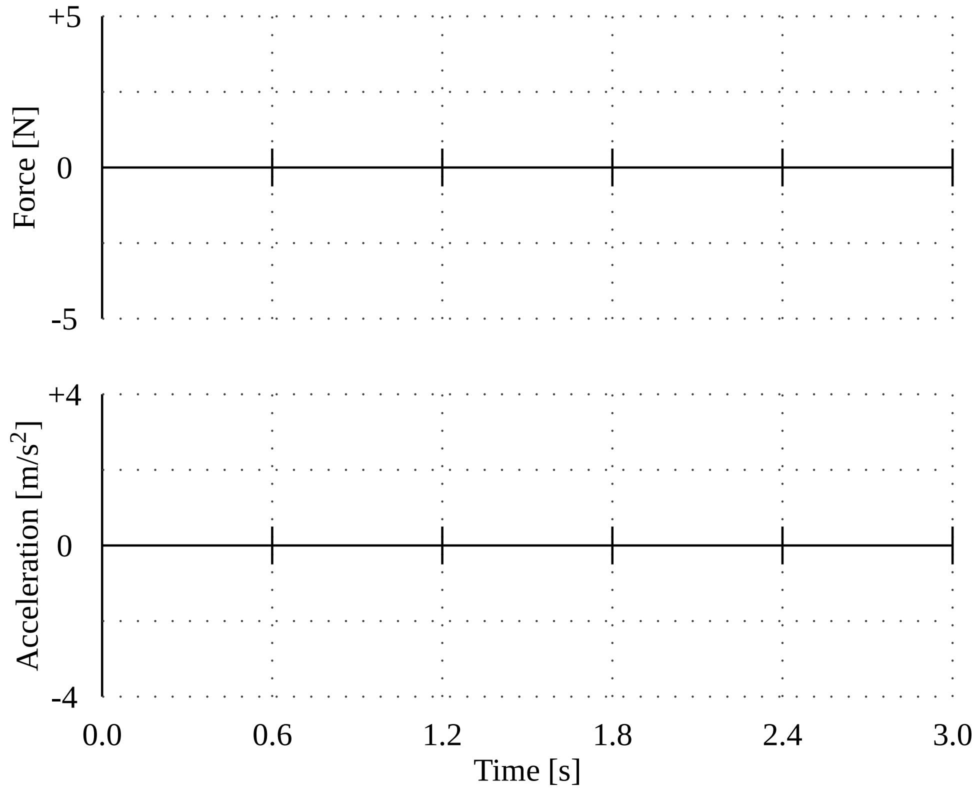
Activity 3.3 Tension and Newton's Second Law

Test your predictions.

1. Use the same setup as for the previous Activity, only replace force probe 2 with a hanging mass, set up the motion detector and plug it into the port labeled *Dig/Sonic 2*.

2. Determine the mass of the cart and force probe:_______ kg

3. Open experiment file *Passive_Forces_A3-3.exp* (*Tension and N2*) to display the axes shown below.



4. Be sure that the motion detector can see the cart all the way to the end of the track.

5. Hang the 100 g mass from the end of the string, and hold the cart at rest at least 0.5 m away from the motion detector.

6. Let the 100 g mass hang without swinging, and then hit *Start*. Hold the cart for the first second after you hear the clicks of the motion detector, and then release it. Be sure to stop the cart before it comes to the end of the track.

7. Sketch your graphs on the axes above. Use arrows on your force and acceleration graphs to indicate the time when the cart was released.

8. Measure the average value of the tension measured by the force probe before the cart was released and while it was accelerating. Also measure the average value of the acceleration during the time interval while the cart had a fairly constant acceleration. (Use *Analysis* and *Statistics...*)

Average tension with cart at rest:_______ N

Average tension with cart accelerating:_______ N

Average acceleration:_______ m/s^2

Comment:

When the cart is released, the cart and hanging mass must both always move with the same velocity since they are connected by the string. Thus the cart and mass must have the same acceleration. According to Newton's Second Law, the combined (net) force on the cart must equal its mass times the acceleration, and the combined (net) force on the hanging mass must equal its mass times the same acceleration.

9. How did the tension while the cart was at rest compare to the weight of the hanging mass? (Hint: remember that $W = mg$.) Did this agree with your prediction? Was the force applied to the end of the string by the hanging mass transmitted undiminished to the cart, as you observed in the previous activity?

10. Did anything happen to the tension after the cart was released? How did the value of the tension as the cart was accelerating compare to the weight of the hanging mass? Did this agree with your prediction?

11. Use Newton's Second Law to explain your answer to the previous question. Why must the tension in the string be smaller than the weight of the hanging mass if the hanging mass is to accelerate?

Lab 7

One-Dimensional Collisions

Pre-Lab: One-Dimensional Collisions

Name:______________________________ Section:______

1. You are driving along the road in a rented moving van that has a mass of 4000 kg. You have just slowed down to 7 m/s (about 15 mph) because you're in a school zone. It's a good thing you thought to do that because a group of first graders are just starting to cross the road. Just as you pass the children you see a 1000 kg sports car in the oncoming lane heading straight for the children at 40 m/s (about 90 mph). Oh no! A desperate thought crosses your mind: you have just enough time to swing into the oncoming lane and speed up a bit before making a head-on collision with the sports car! Assuming that the collision is *inelastic*, how fast do you need to go to stop the sports car? Can you save the children?

2. Suppose somebody tosses you a raw egg and you catch it.

    a) If the egg has mass m and is heading toward your hand at speed v, what is the change in its momentum when you catch it? What is the impulse from your hand? Does your answer depend on whether you catch the egg gently or not?

    b) Suppose the time you take to bring the egg to a stop is Δt. Would you rather catch the egg in such a way that Δt is small or large. Why?

    c) How is the average force, F, exerted on the egg related to the time it takes to catch the egg, Δt?

3. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

4. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

One-Dimensional Collisions

> In any system of bodies which act on each other, action and reaction, estimated by momentum gained and lost, balance each other according to the laws of equilibrium.
>
> Jean de la Rond D'Alembert

Objectives

- To understand the definition of momentum and its vector nature as it applies to one-dimensional collisions.
- To develop the concept of impulse to explain how forces act over time when an object undergoes a collision.
- To study the interaction forces between objects that undergo collisions.
- To examine the relationship between impulse and momentum experimentally in elastic and inelastic collisions.

Newton's First Law of Motion

Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed on it.

Newton's Second Law of Motion

The [rate of] change of motion is proportional to the motive force impressed: and is made in the direction of the right line in which that force is impressed.

Overview

In this lab we will explore the forces of interaction between two objects and study the changes in motion that result from these interactions. We are especially interested in studying collisions in which interactions take place in fractions of a second or less. Early investigators spent a considerable amount of time trying to observe collisions, but they encountered difficulties. This is not surprising, since the observation of the details of such phenomena requires the use of instrumentation—such as high speed cameras—that was not yet invented.

However, the principles describing the outcomes of collisions were well understood by the late seventeenth century when several leading European scientists including Isaac Newton developed the concept of *quantity-of-motion* to describe both *elastic collisions* in which objects bounce off each other and *inelastic collisions* in which objects stick together. These days we use the word *momentum* rather than *quantity-of-motion* in describing collisions and explosions.

We will begin our study of collisions by exploring the relationship between the forces experienced by an object and its momentum change. It can be shown mathematically from Newton's laws, and experimentally from our own observations, that the change in momentum of an object is equal to a quantity called *impulse*

$$\vec{J} = \Delta\vec{p} \ .$$

Impulse is a quantity which takes into account both the magnitude of the applied force at each instant in time, and the time interval over which this force acts. The statement of equality between impulse and momentum change is known as the *impulse–momentum theorem*.

Momentum is defined by the vector equation

$$\vec{p} = m\vec{v} \ .$$

Originally Newton did not use the concept of acceleration or velocity in his laws. Instead he used the term "motion" which he defined as the product of mass and velocity (the quantity we now call momentum). See the sidebars for a translation from Latin of Newton's first two laws with some parenthetical changes for clarity[1,2].

[1] I. Newton, *Principia Mathematica*, Florian Cajori, Ed. (U. of Calif. Press, Berkeley, 1934). p. 13.

[2] L. W. Taylor, *Physics the Pioneer Science*, Vol. 1 (Dover, New York, 1959). pp. 129-131.

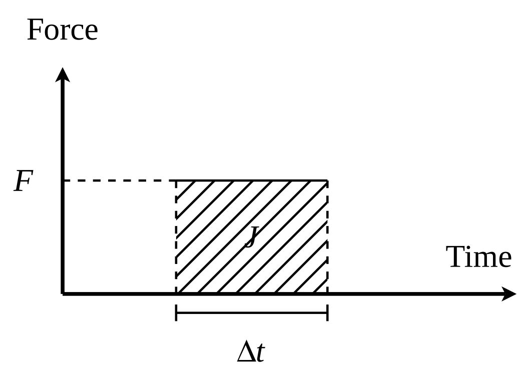
The more familiar contemporary statement of the Second Law is that the net force on an object can be calculated as the product of its mass and its acceleration where the direction of the force and of the resulting acceleration are the same. Newton's statement of the law and the more modern statement are mathematically equivalent.

In physics the *change* in momentum is related to a quantity called the impulse. The impulse depends on the force acting during the collision process and the time over which that collision force acts. We cannot just look at the maximum force exerted, however. You can see this from a simple experiment tossing raw eggs. We will do it as a thought experiment to avoid the mess! Suppose somebody tosses you a raw egg and you catch it. What is the relationship between the force you have to exert on the egg to stop it, the time it takes you to stop it and the momentum change that the egg experiences? You ought to have some intuition about this matter. In more ordinary language, would you catch an egg slowly (by relaxing your hands and pulling them back) or quickly (by holding them rigidly)?

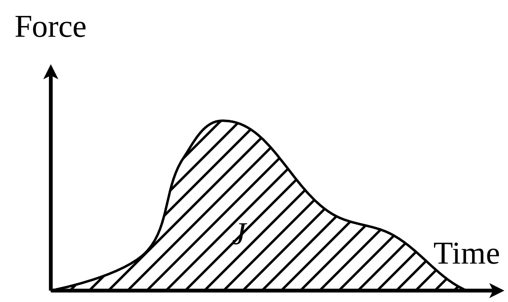
In bringing an egg to rest, the change in momentum (or impulse) is the same whether you use a large force during a short time interval or a small force during a long time interval. Of course, which one you choose makes a lot of difference in whether the egg breaks or not! In one dimension, for a *constant* force, F, acting over a time interval, Δt, the impulse is

$$J = F\Delta t \ .$$

Graphically, J is the area of a rectangle with height F and width Δt, shown in the graph below.



As you can imagine, a large force acting over a short time and a small force acting over a long time can have the same impulse (area). If the applied force is not constant, then the impulse can still be calculated as the area under the force vs. time graph (this is technically the integral of F with respect to t).



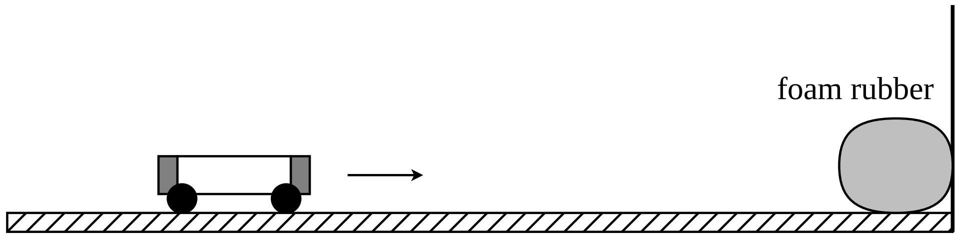
Part I Impulse, Momentum and Collisions

Let's first see qualitatively what an impulse curve might look like in a real collision in which the forces change over time during the collision. To explore this idea you will need:

- Cart
- Smooth level ramp or other level surface
- Computer
- Motion detector
- Force probe with rubber stopper
- Soft foam rubber

Activity 1.1 Observing Collision Forces that Change with Time

1. Place the foam rubber at the end of the track and against the wall. Collide the cart into the foam rubber several times, and observe what happens. It's okay if the force probe is already mounted on the cart.

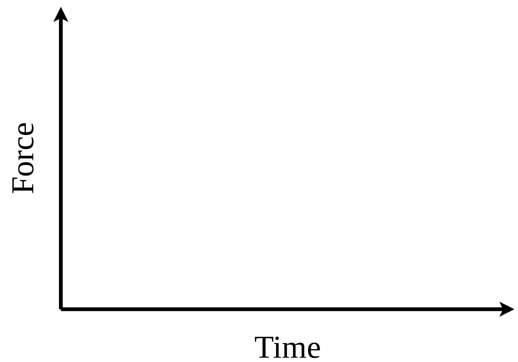


2. If friction is negligible, what is the net force exerted on the cart just before it starts to collide?

3. When is the magnitude of the force on the cart a maximum, in terms of the cart's velocity and the compression of the foam rubber?

4. Roughly how long does the collision process take? A fraction of a second? A second? Several seconds?

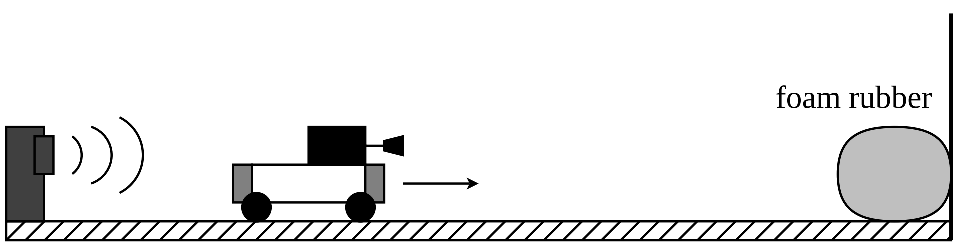
5. Remembering what you observed, attempt a rough sketch of the shape of the force the wall exerts on the cart as a function of time during the collision.



Activity 1.2 Examining the Impulse-Momentum Theorem in a Nearly Elastic Collision

During the collision the force is not constant. In order to measure the impulse and compare it to the change in momentum of the cart, you must 1) plot a force-time graph, and find the area under it, and 2) measure the velocity of the cart before and after the collision with the wall. Fortunately the force probe, motion detector and software will allow you to do this. The force probe will be mounted on the cart to measure the force applied to the cart.

1. Fasten the force probe to the cart if it's not already present. Set up the motion detector as shown. Be sure that the ramp is level.

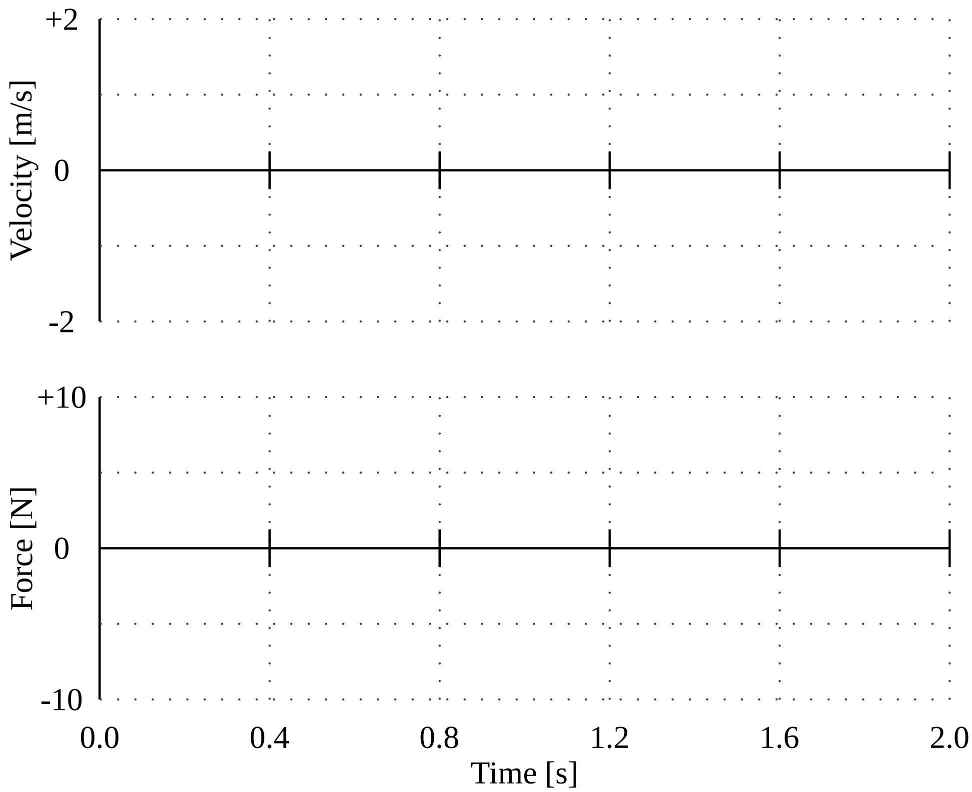


2. Measure the mass of the cart.

   $m =$______ kg

3. Open the experiment *One-Dimensional_Collisions_A1-2.exp* (*Impulse and Momentum*) to display the following axes. This experiment has been set

up to record force and motion data. It has also been set up to record a push on the force probe as a positive force, and velocity towards the motion detector (away form the foam rubber) as positive.



4. Calibrate the force probe with a 0.50 kg mass for a push (enter negative numbers).

5. Be sure that the wire from the force probe is out of the way, so that it won't be detected by the motion detector. Practice pushing the cart toward the foam rubber, and watching it bounce off. (Small pushes are best.) Find a way to push without putting your hand between the motion detector and the cart. When you are ready, click *Start*. As soon as you hear the clicking of the motion detector, give the cart a push. Repeat until you get a good set of graphs, i.e., the motion detector saw the relatively constant velocities of the cart as it moved toward the stopper and as it moved away, and also the maximum force was no more than 10 N. (With too large a force, the force probe will read inaccurately.)

6. Does the shape of the force-time graph agree with your sketched prediction? Explain.

7. Measure the average velocity of the cart as it approached the stopper, and the average velocity as it moved away from the stopper. (Use *Statistics* on the *Analysis* menu.) Don't forget to include a sign. Positive velocity should be away from the wall (foam rubber).

   Average velocity toward the wall: ______ m/s

   Average velocity away from the wall: ______ m/s

8. Calculate the change in momentum of the cart. Show your calculations.

   $\Delta p =$______ kg m/s

9. Now you need to find the area under the force-time graph—the impulse. The area under a curve is the same as the *integral* of force vs. time. Click once on the force graph to select it. Use the mouse to highlight the region of the force-time graph during the collision. Then select the *Integral* button from the menu bar, and the area will be displayed above the graph.

   $J =$______ N s

   (note: 1 N s = 1 kg m/s)

10. Sketch your graphs on the axes on the previous page.

11. Did the calculated change in momentum of the cart equal the measured impulse applied to it by the foam rubber during the nearly elastic collision? Explain.

12. What would the impulse be if the initial momentum of the cart were larger?

13. What if the collision were inelastic rather than elastic, i.e. what if the cart stuck to the stopper after the collision?

14. Using the two definitions of impulse that we looked at in this lab, derive Newton's Second Law. Hints: $\Delta p = m\Delta v$ and $a = \Delta v/\Delta t$.

Lab 8

Newton's Third Law and Conservation of Momentum

Pre-Lab: Newton's Third Law and Conservation of Momentum

Name:______________________________ Section:______

1. What is Newton's Third Law?

2. A person jumps straight up. While they are pushing against the ground with their feet, is the normal force of the ground against their feet larger, smaller, or the same as their weight. Does this conflict with Newton's Third Law?

3. How could you measure the average momentum of an object using a velocity-time graph? Is there any other piece of information that you would need?

4. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

5. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Newton's Third Law and Conservation of Momentum

> To every action there is always opposed an equal reaction, or the mutual actions of two bodies upon each other are always equal, and directed to contrary parts. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may say so) will be equally drawn back towards the stone . . . .
>
> Isaac Newton

Objectives

- To study the forces between objects that undergo collisions and other types of interactions with each other.
- To examine the consequences of Newton's Third Law as applied to interaction forces between objects.

- To formulate the Law of Conservation of Momentum as a theoretical consequence of Newton's Third Law and the impulse-momentum law.

Overview

In *One-Dimensional Collisions*, you looked at the definition of momentum, and examined the momentum changes of objects undergoing collisions. We focused our attention on the momentum change that an object undergoes when it experiences a force that is extended over time (even if that time is very short!). You also looked at the forces acting on objects during collisions, and examined the impulse-momentum law which compares the change in momentum to the impulse.

Since interactions like collisions and explosions never involve just one object, we would like to turn our attention to the mutual forces of interaction between two or more objects. This will lead us to a very general law known as *Newton's Third Law* which relates the forces of interaction exerted by two objects on each other. Then, you will examine the consequences of this law and the impulse-momentum law which you examined in the last lab, when they are applied to collisions between objects. In doing so, you will arrive at one of the most important laws of interactions between objects, the Conservation of Momentum Law. As usual you will be asked to make some predictions about interaction forces and then be given the opportunity to test these predictions.

Part I Forces between interacting Objects

There are many situations where objects interact with each other, for example, during collisions. In this investigation we want to compare the forces exerted by the objects on each other. In a collision, both objects might have the same mass and be moving at the same speed, or one object might be much more massive, and they might be moving at very different speeds. What factors might determine the forces between the objects? Is there some general law which relates these forces? To make these observations you will need the following equipment:

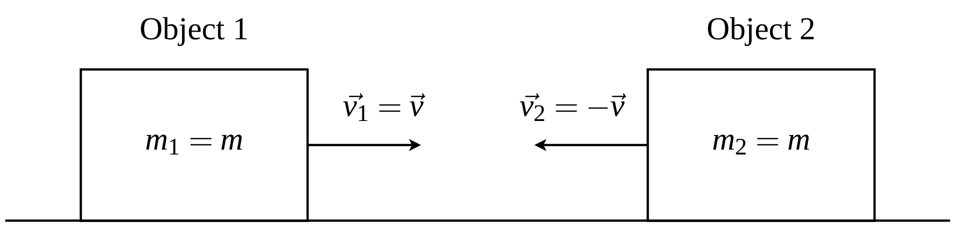
- Two force probes
- Computer
- 500 gram masses to calibrate the force probes

- Two low-friction carts
- Masses to place on one of the carts to double and triple its mass
- Smooth level track or other level surface

Activity 1.1 Collision Interaction Forces

What can we say about the forces two objects exert on each other during a collision?

1. Suppose the masses of two objects are the same and that the objects are moving toward each other at the same speed so that $m_1 = m_2$ and $\vec{v}_1 = -\vec{v}_2$ (same speed, opposite direction).



   Predict the relative magnitudes of the forces between object 1 and object 2 during the collision. Place a check next to your prediction:

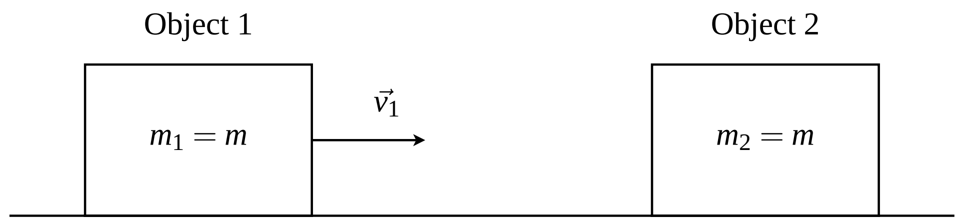
   ______object 1 exerts a larger force on object 2

   ______the objects exert the same force on each other

   ______object 2 exerts a larger force on object 1

2. Suppose the masses of two objects are the same and that object 1 is moving toward object 2, but object 2 is at rest.

$$m_1 = m_2, \quad \vec{v}_1 > 0, \quad \vec{v}_2 = 0$$

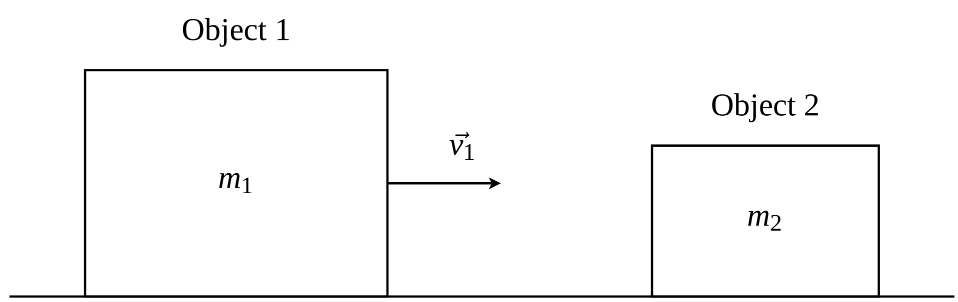


Predict the relative magnitudes of the forces between object 1 and object 2 during the collision:

_______object 1 exerts a larger force on object 2
_______the objects exert the same force on each other
_______object 2 exerts a larger force on object 1

1. Suppose the mass of object 1 is greater than that of object 2 and that it is moving toward object 2 which is at rest.

$$m_1 > m_2, \quad \vec{v}_1 > 0, \quad \vec{v}_2 = 0$$



Predict the relative magnitudes of the forces between object 1 and object 2 during the collision:

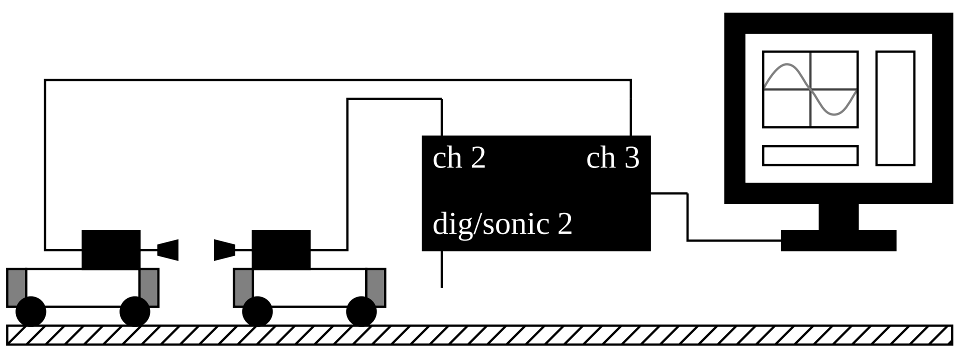
_______object 1 exerts a larger force on object 2

_______the objects exert the same force on each other

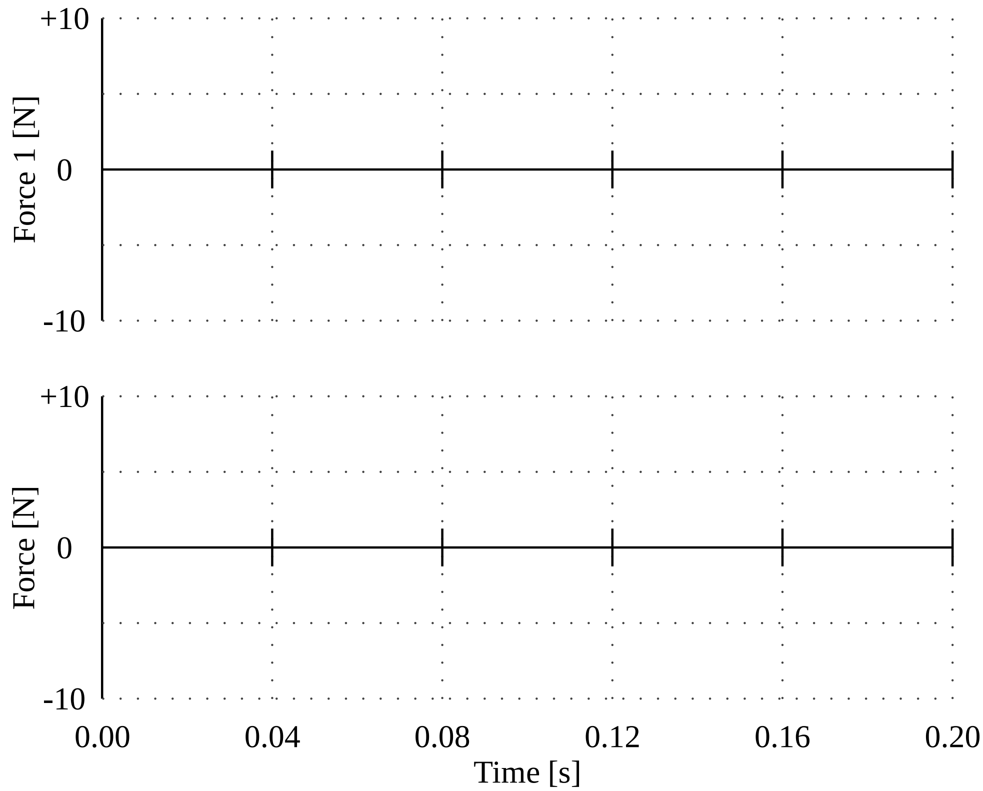
_______object 2 exerts a larger force on object 1

2. Provide a summary of your predictions. What are the circumstances under which you predict that one object will exert a greater force on the other object?

3. In order to test the predictions you made you can study gentle collisions between two force probes attached to carts. You should add additional masses to one of the carts to increase its total mass so it has significantly more mass than the other. Set up the apparatus as shown in the following diagram. The force probes should be securely fastened to the carts. The hooks should be protected by rubber stoppers which should be carefully aligned so that they will collide head-on with each other.



4. Open the experiment *Newtons_Third_Law_A1-1.exp* (*Collisions*) to display the axes shown below. The software will then be set up to measure the forces applied to each probe with a very fast data collection rate. (This allows you to see all of the details of the collision which takes place in a very short time interval.)



5. Calibrate the force probes one at a time. One should be calibrated to read positive forces, and the other to read negative forces (enter a negative number when calibrating). The reason you do this is because the two force probes will be pointing in opposite directions.

6. Use the two carts to explore various situations which correspond to the predictions you made about interaction forces. Your goal is to find out under what circumstances one object exerts more force on another object. Try collisions (a) - (c) listed below. Be sure that the forces during the collisions do not exceed 20 N. Sketch the graphs for each collision on the axes above. Be sure to label your graphs. For each collision also find the values of the impulses exerted by each cart. Record these values in the spaces below.

   a) Two carts of the same mass moving towards each other at about the same speed.

      $\vec{J}_1 =$______ $\hat{i}$ N s $\vec{J}_2 =$______ $\hat{i}$ N s

b) Two carts of the same mass, one at rest and the other moving towards it.

$\vec{J}_1 =$______ $\hat{i}$ N s $\vec{J}_2 =$______ $\hat{i}$ N s

c) One cart twice or three times as massive as the other, moving toward the other cart which is at rest.

$\vec{J}_1 =$______ $\hat{i}$ N s $\vec{J}_2 =$______ $\hat{i}$ N s

7. How are the two different values related to each other?

8. Did your observations agree with your predictions? What can you conclude about forces of interaction during collisions? Under what circumstances does one object experience a different force than the other during a collision? How do forces compare on a moment by moment basis during each collision?

9. Which of Newton's three laws does this impulse data support? State the law.

10. How does the vector impulse due to cart 1 acting on cart 2 compare to the impulse of cart 2 acting on cart 1 in each collision? Are they the same in magnitude or different? Do they have the same sign or a different sign?

Activity 1.2 Other Interaction Forces

Interaction forces between two objects occur in many other situations besides collisions. For example, suppose that a small car pushes a truck with a stalled engine. The mass of object 1 (the car) is much smaller than object 2 (the truck).

At first the car doesn't push hard enough to make the truck move. Then, as the driver pushes down harder on the gas pedal, the truck begins to accelerate. Finally the car and truck are moving along at the same constant speed.

1. Place a check next to your predictions of the relative magnitudes of the forces between objects 1 and 2.

   a) Before the truck starts moving:
      ______the car exerts a larger force on the truck
      ______the car and truck exert the same force on each other
      ______the truck exerts a larger force on the car

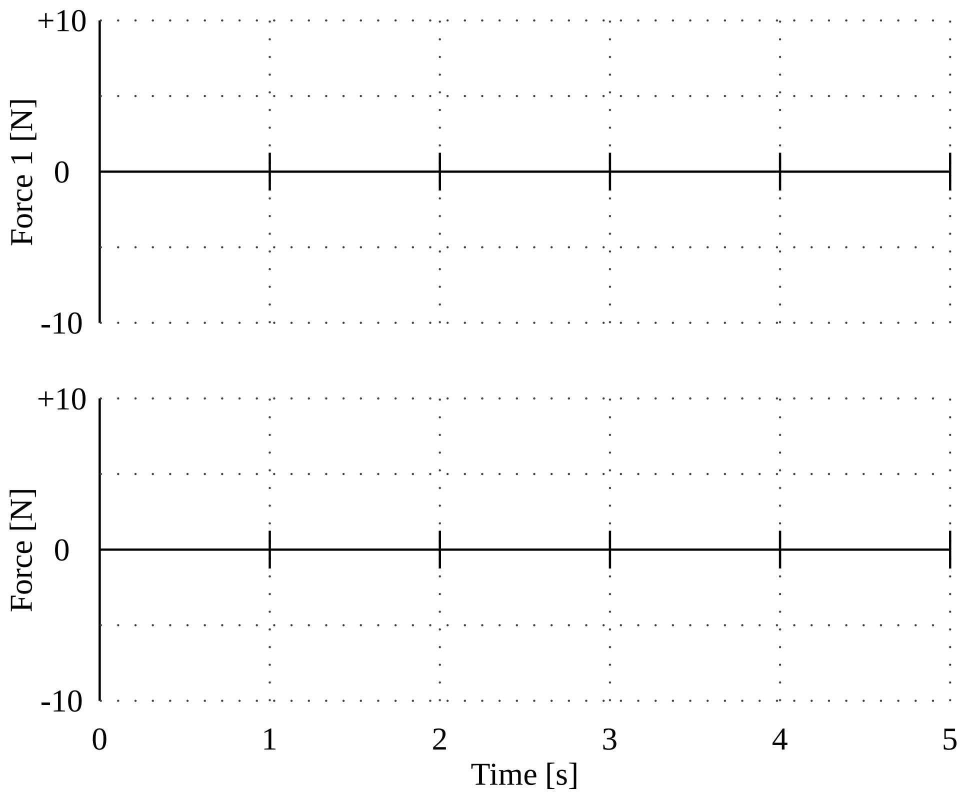
   b) While the truck is accelerating:
      ______the car exerts a larger force on the truck
      ______the car and truck exert the same force on each other
      ______the truck exerts a larger force on the car

   c) After the car and truck are moving at a constant speed:
      ______the car exerts a larger force on the truck
      ______the car and truck exert the same force on each other
      ______the truck exerts a larger force on the car

2. Test your predictions. Change the program to display the two force probes at a slower data rate of 20 data points per second.

3. Use the same setup as in the last activity with the two force probes mounted on carts. Add masses to cart 2 (the truck) to make it much more massive than cart 1 (the car).

4. Your hand will be the engine for cart 1. Move the carts so that the stoppers are touching, and then hit *Start*. When graphing begins, push cart 1 toward the right. At first hold cart 2 so it cannot move, but then allow the push of cart 1 to accelerate cart 2, so that both carts move toward the right. Sketch your graphs on the axes below.



5. What are the force readings at these points:

   a) Starting push
   Force 1 = ______ N   Force 2 = ______ N

b) Right before the second cart is released
Force 1 = ______ N Force 2 = ______ N

c) As the two carts are moving together
Force 1 = ______ N Force 2 = ______ N

6. How do your results compare to your predictions? Is the force exerted by cart 1 on cart 2 (reading of force probe 2) significantly different from the force exerted by cart 2 on cart 1 (reading of force probe 1) during any part of the motion? Explain any differences you observe between your predictions and your observations.

Part II Newton's Laws and Momentum Conservation

Your previous work should have shown that interaction forces between two objects are equal in magnitude and opposite in sign (direction) on a moment by moment basis for all the interactions you might have studied. This is a testimonial to the seemingly universal applicability of *Newton's Third Law* to interactions between objects.

As a consequence of the forces being equal and opposite at each moment, you should have seen that the impulses of the two forces were always equal in magnitude and opposite in direction. You may have seen in lecture or in your text a derivation of the *Conservation of Momentum Law* by combining these findings with the impulse-momentum theorem (which is really another form of *Newton's Second Law* since it is derived mathematically from the *Second Law*). The argument is that the impulse $\vec{J}_1$ acting on cart 1 during the collision equals the change in momentum of cart 1, and the impulse $\vec{J}_2$ acting on cart 2 during the collision equals the change in momentum of cart 2:

$$\vec{J}_1 = \Delta\vec{p}_1, \qquad \vec{J}_2 = \Delta\vec{p}_2 \ .$$

But, as you have seen, if the only forces acting on the carts are the interaction forces between them, then $\vec{J}_1 = -\vec{J}_2$. Thus, by simple algebra

$$\Delta\vec{p}_1 = -\Delta\vec{p}_2 \quad \text{or} \quad \Delta\vec{p}_1 + \Delta\vec{p}_2 = 0 \ ,$$

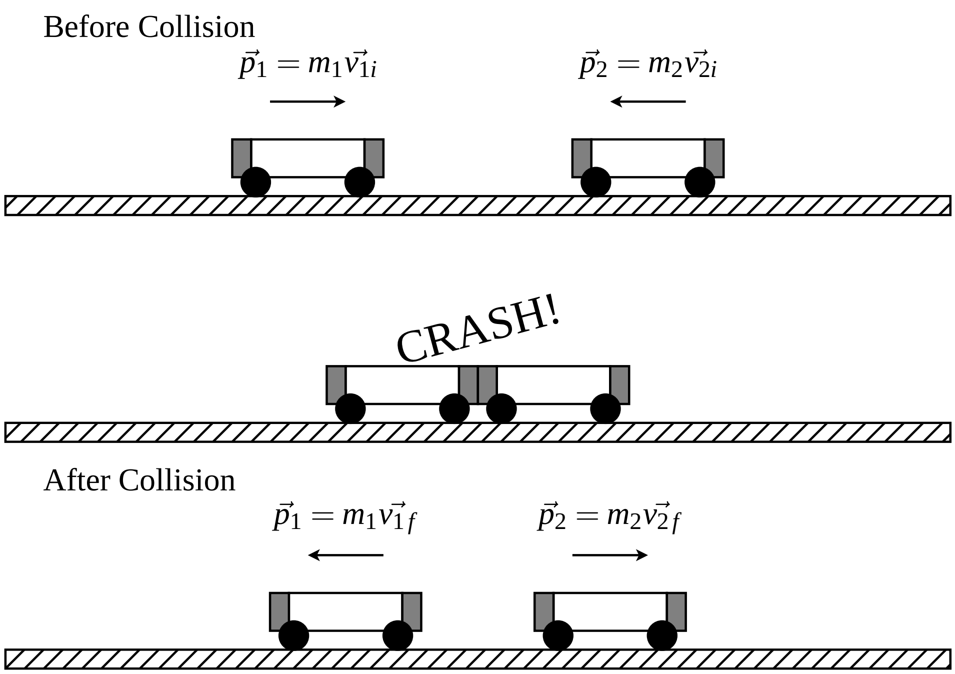
i.e., there is no change in the total momentum $\vec{p}_1 + \vec{p}_2$ of the system (the two carts).

If the momenta of the two carts before (subscript i) and after (subscript f) the collision are represented as in the diagrams below, then

$$\vec{p}_f = \vec{p}_i \ ,$$

where

$$\vec{p}_i = m_1\vec{v}_{1i} + m_2\vec{v}_{2i} \tag{8.1}$$
$$\vec{p}_f = m_1\vec{v}_{1f} + m_2\vec{v}_{2f} \ . \tag{8.2}$$

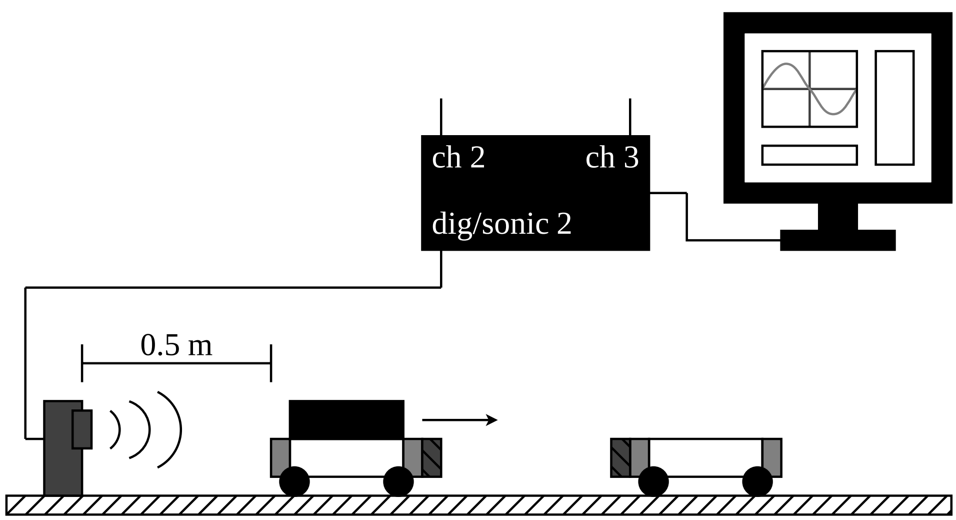


In the next activity you will examine if momentum is conserved in one simple collision—an *inelastic* collision between two carts of unequal mass. You will need the following:

- Two low friction carts
- Motion detector
- Computer
- Masses to place on one of the carts to double its mass
- Smooth level track or other level surface

Activity 2.1 Conservation of Momentum in an Inelastic Collision

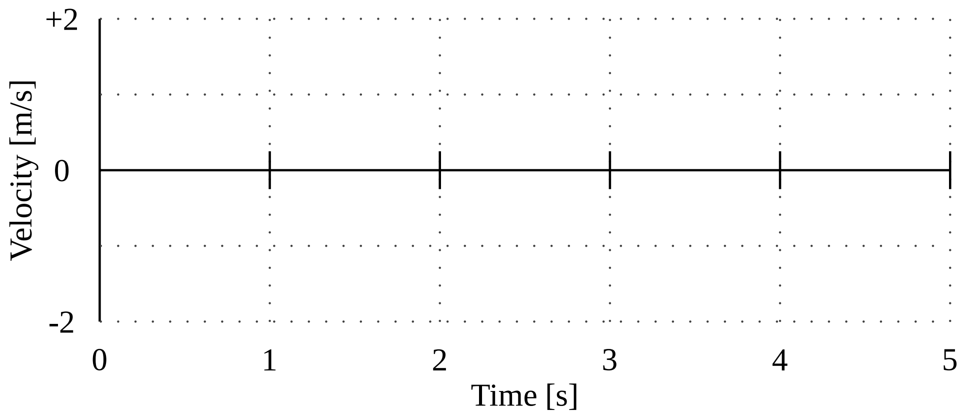
1. Set up the carts, track and motion detector as shown below. Remove the force probes from the carts, and place loops of tape or Velcro on them so that they will stick together after the collision. Add masses to cart 1 so that it is about twice as massive as cart 2.



2. Measure the masses of the two carts.

   $m_1 =$______ kg $m_2 =$______ kg

3. Unplug the force probes, and plug the motion detector into channel *Dig/Sonic 2* of the *LabPro* device. Open the experiment *Newtons_Third_Law_A2-1.exp* (*Inelastic Collision*). The axes shown below should be displayed.



4. You are going to give the more massive cart 1 a push and collide it with cart 2 which is initially at rest. The carts will stick together after the collision. Suppose that you measure the total momentum of cart 1 and cart 2 before and after the collision. How do you think that the total momentum after the collision will compare to the total momentum before the collision. Explain the basis for your prediction.

5. Test your prediction. Begin with cart 1 at least 0.50 m from the motion detector. Press *Start*, and when you hear the clicks of the motion detector, give cart 1 a brisk push toward cart 2 and release it. Be sure that the motion detector does not see your hand. Repeat until you get a good run when the carts stick, and move together after the collision. Sketch the graph.

6. Use *Statistics* on the *Analysis* menu to measure the velocity of cart 1 just before the collision, and the velocity of the two carts together just after the collision. You may want to find the average velocities over short time

Comment:

Momentum is conserved whether or not the two carts stick to one another after the collision, but to test this you would need to measure the velocities of both carts after the collision. Momentum is also conserved if both carts are moving before the collision.

intervals just before and just after the collision. (Highlight these intervals with the mouse button held down, and then use *Statistics...* on the *Analysis* menu.)

$\vec{v_1}_i =$______ $\hat{i}$ m/s $\quad$ $\vec{v_1}_f =$______ $\hat{i}$ m/s

7. Calculate the total momentum of carts 1 and 2 before the collision and after the collision using eqs. (10.1) and (10.2). Show your calculations below.

$\vec{P}_i =$______ $\hat{i}$ kg m/s $\quad$ $\vec{P}_f =$______ $\hat{i}$ kg m/s

8. Was momentum conserved during the collision? Did your results agree with your prediction? Explain.

9. What were the difficulties in doing this last experiment which might cause errors in the results?

Lab 9

Work and Energy

Pre-Lab: Work and Energy

Name:______________________________ Section:______

1. Does effort necessarily result in physical work? Suppose two professors are in an evenly matched tug of war. They are obviously expending effort to pull on the rope, but according to the definition of physical work, are they doing any physical work? Explain.

2. A wooden block with a mass of 0.30 kg is pushed along a frictionless sheet of ice with a constant external force of 10 N which acts in a horizontal direction. After it moves a distance of 0.40 m how much work has been done on the block by the external force?

3. The same wooden block with a mass of 0.30 kg is pushed along a table with a constant external force of 10 N which acts in a horizontal direction. It moves a distance of 0.40 m. However, there is a friction force opposing its motion. The coefficient of kinetic friction, μ_k, is 0.20.

   a) According to the definition of work done by a force and work done against a force, what is the work associated with the external force? Is work done by this force or against it? Is the work positive or negative?

   b) According to the definition of work, what is the work associated with the friction force? Is work done by the friction force or against it? Is the work positive or negative?

4. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

5. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Work and Energy

> I don't want to achieve immortality through my work... I want to achieve it through not dying.
>
> Woody Allen

Objectives

- To extend the intuitive notion of work as physical effort to a formal mathematical definition of work as a function of force and distance.
- To develop an understanding of the physical significance of work when force is not constant.

Overview

In order to understand the effects of various types of interactions, it is helpful to develop two new concepts: *work* and *energy*. These concepts can be related by Newton's laws to force, distance, and velocity. In this unit, you will begin the process of understanding the scientific definitions of work and energy.

Part I Physical Work

In physics, work is not simply effort. In fact, the physicist's definition of work is precise and mathematical. In order to have a full understanding of how work is defined in physics, we need to consider its definition in a very simple situation and then enrich it later to include more realistic situations.

If an object that is moving in a straight line experiences a constant force in the direction of its motion during the time it is undergoing a displacement, the work done by the external force, F_{ext}, is defined as the product of the force and the displacement of the object:

$$W = F_{\text{ext}} \Delta x \ ,$$

where W represents the work done by the external force, F_{ext} is the magnitude of the force, and Δx the displacement of the object. Work *done by* a force is always *positive*!

What if the force of interest and the displacement are in the opposite direction? For instance, what about the work done against the force of sliding friction, F_f, when a block slides down an inclined plane as a result of the gravitational force? In this case we refer to work done against a force. This is given by

$$W_{\text{against}} = -F_f \Delta x \ .$$

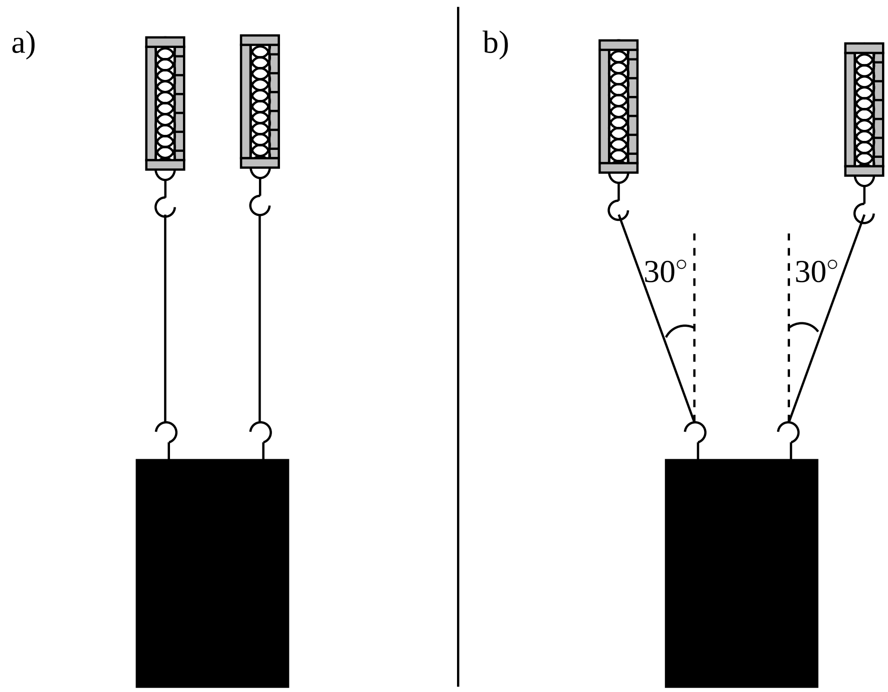
Work *done against* a force is always *negative*!

Let's be more quantitative about measuring force and distance and calculating the work. How should work be calculated when the external force and the displacement of an object are not in the same direction? For this project you'll need:

- Two spring scales
- Wood block with hooks in it
- String
- Protractor

Activity 1.1 Calculating Work

1. Pass a piece of string through the hooks on the block and tie each end to a spring scale. Suspend the block so that the strings are vertical as shown in side a) of the following figure.



2. Practice lifting the block slowly over a vertical distance of 0.5 m with a constant speed, keeping the strings vertical. Record the sum of the spring scale readings (the total upward force) as you do this and write the force in newtons and the distance in meters below and calculate the work done on the block in joules. (Note that there is a special unit for work—the joule or J for short. One joule is equal to one newton times one meter, i.e. J = N·m).

   $F =$______ N $\Delta x =$______ m

   $W =$______ J

3. How do the spring scale readings compare to the *weight* of the block?

4. Repeat the measurement, only this time lift the block so that each string makes a 30° angle with respect to the vertical as you lift it, as shown on side b) of the previous figure. Lift the block assembly at a constant slow speed, reading the scales as the block is lifted. Record your measurements below.

   $F =$______ N $\Delta x =$______ m

5. Was the force measured with the angled strings different than the force measured when the strings were vertical? If so how?

6. Assuming that the actual physical work done in both cases was the same, how could you enhance the mathematical definition of work so that the forces measured for the angled strings could be used to calculate work? In other words, use your data to postulate a mathematical equation that relates the physical work, W, to the magnitude of the applied force, F, the magnitude of the displacement, Δx, and the angle, θ, between F and Δx. Explain your reasoning. Hint: $\sin 30^\circ = 0.5$, $\cos 30^\circ = 0.865$.

Part II Work and Kinetic Energy

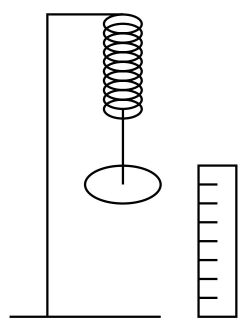
So far we have lifted an object with a constant force and calculated the work needed to displace that object. In most real situations the force on an object can change as it moves.

What happens to the average force needed to stretch a spring from 0 to 1 cm compared to the average force needed to extend the same spring from 3 to 4 cm? How does the applied force on a spring affect the amount by which it stretches, i.e. its displacement? You will need:

- Mounted spring
- Ruler (may be part of the spring mounting)
- Mass pan
- Nine 50 g weights (a total of 450 g)
- Spreadsheet program (*Excel*)

Activity 2.1 The Force and Work Needed to Stretch a Spring

1. Setup the the experiment as shown below.

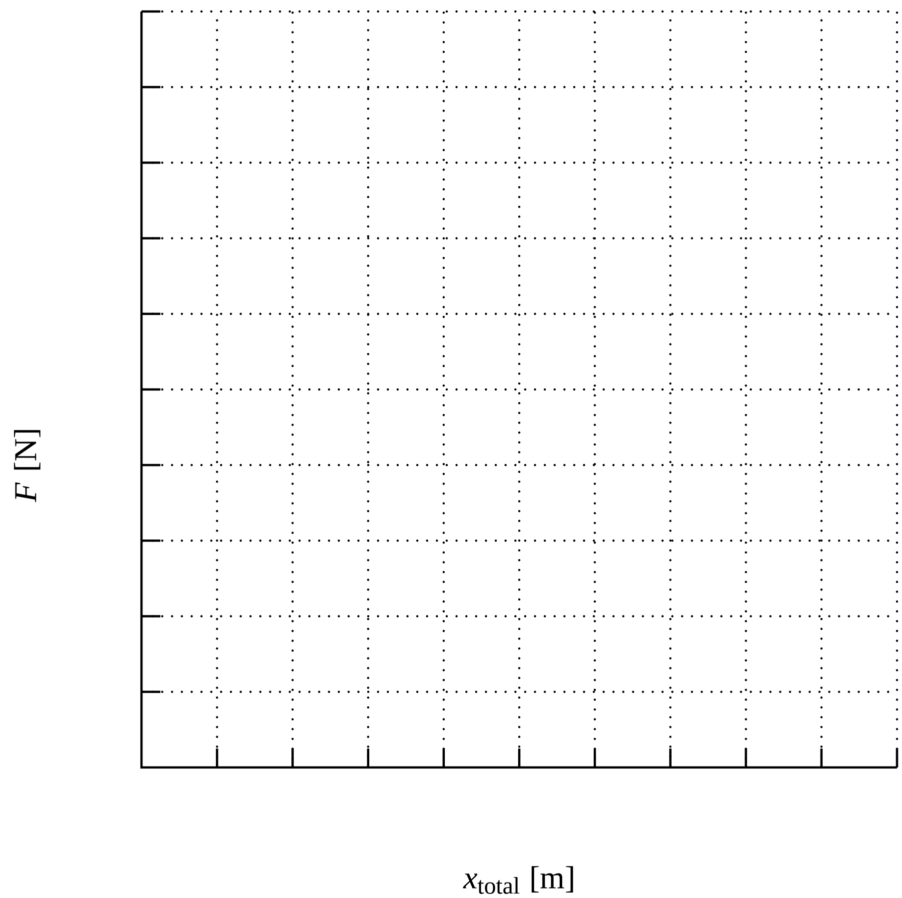


2. Extend the spring from 0 to 1 cm. Feel the force needed to extend the spring. Extend the spring from 3 to 4 cm. Feel the force needed to extend the spring again. How do the two forces compare? Are they the same? Does the force needed to stretch a spring depend on how much it has already been stretched?

3. Add the 50 g weights one at a time. As you add each weight, you increase the force on the spring, $F = m_{\text{total}} g$. This causes the spring to stretch an additional amount Δx to a total displacement x_{total}. Fill in F, Δx, and x_{total} in the table below. Also calculate the work done by each individual weight, $\Delta W = F\Delta x$.

F [N]	Δx [m]	x_{total} [m]	ΔW [J]
0	0	0	—

4. Make a plot of F with respect to x_{total} in *Excel*. Also draw the graph on the following axes (you'll need it in a few steps).



5. Is the graph linear? Is this consistent with your findings in Step 2?

6. In *Excel*, add a *trend line* to find the slope of the curve. Use the symbol k to represent the slope. What is the value of k? What are its units? Note: k is commonly called the *spring constant*.

7. Write the equation describing the relationship between the external force, F, and the total displacement, x_{total}, of the spring using the symbols F, k, and x_{total}. Note: this is equation is known as *Hooke's Law*.

Activity 2.2 Calculating Work when the Force is not Constant

How can we calculate the total work done in stretching the spring? We can use several equivalent techniques:

- Summing the ΔW $(W_{\text{total}} = \Sigma \Delta W)$.
- Finding the area under the curve of F vs. x_{total}.
- Using mathematical integration.

All three methods should yield about the same result.

1. Calculate the work needed to stretch the spring to a distance $D = 3$ cm by adding up the small increments of ΔW.

   $W_{\text{total}} = \sum \Delta W =$ ______ J

2. Calculate the work needed to stretch the spring to a distance $D = 3$ cm by computing the area under the curve in the graph of F vs. x_{total} that you just created.

   $W_{\text{total}} =$ ______ J

3. How do your answers compare to the value of the actual integral?

   $\int_0^D kdx = \frac{1}{2}kD^2 =$ ______ J

Lab *10*

Energy Conservation

Pre-Lab: Energy Conservation

Name:________________________________ Section:______

1. What does it mean for a physical quantity to be *conserved*? Give an example of something that is conserved and something that is not.

2. In general, is kinetic energy conserved? Why or why not?

3. Based on energy conservation, is a “perpetual motion” machine possible? Why or why not?

4. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

5. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Energy Conservation

> In order to understand the equivalence of mass and energy, we must go back to two conservation principles which. . . held a high place in pre-relativity physics. These were the principle of the conservation of energy and the principle of the conservation of mass.
>
> Albert Einstein

Objectives

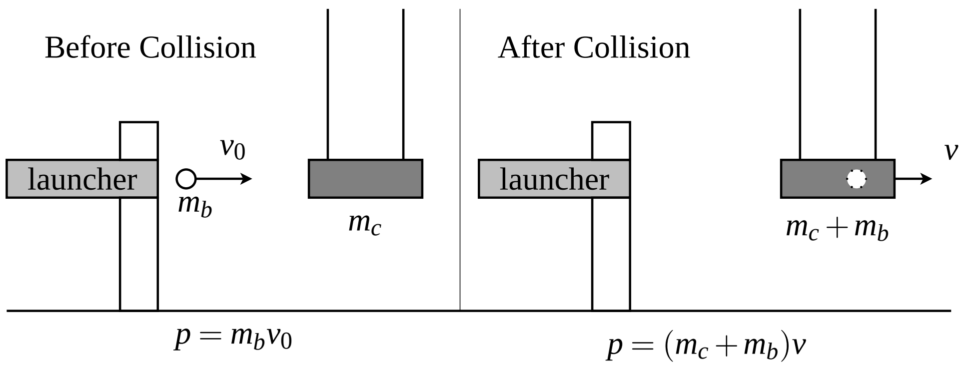
- To understand the concept of potential energy.
- To investigate the conditions under which mechanical energy is conserved.

Overview

A ball is launched horizontally and embeds in the bob of a pendulum. The pendulum then swings up to a particular height, h. Momentum is conserved during the collision, but kinetic energy is not. The momentum after the collision is equal to the momentum before the collision

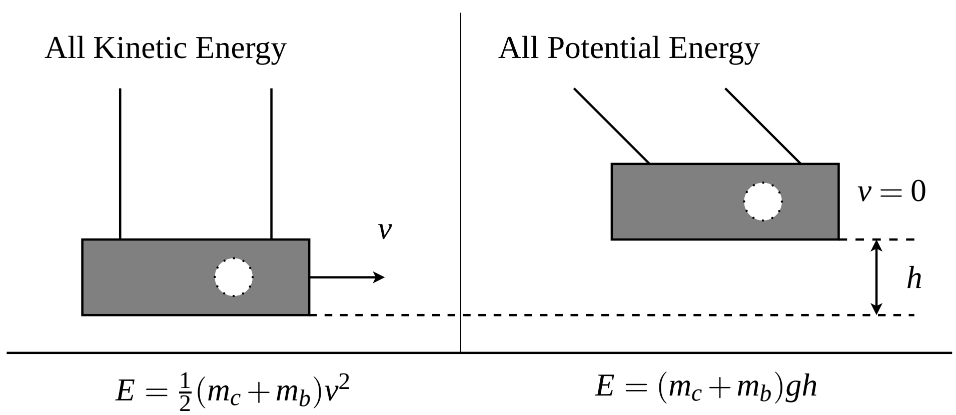
$$m_b v_0 = (m_c + m_b)v \ , \tag{10.1}$$

where m_b is the mass of the ball, v_0 is the muzzle velocity of the ball, m_c is the mass of the catcher, and v is the velocity of the catcher (and ball) after the collision.



The kinetic energy of the catcher (and ball) after the collision is converted completely to potential energy at the top of the swing:

$$\frac{1}{2}(m_c + m_b)v^2 = (m_c + m_b)gh \ . \tag{10.2}$$



To find the muzzle velocity of the ball, we begin with the potential energy of the pendulum at the top of its swing and work backwards from there. From our equation for energy conservation (7.2),

$$v = \sqrt{2gh} \ . \tag{10.3}$$

Substituting the above into the equation for momentum conservation (7.1),

$$m_b v_0 = (m_c + m_b)\sqrt{2gh}$$

$$v_0 = \left(\frac{m_c + m_b}{m_b}\right)\sqrt{2gh}\ . \tag{10.4}$$

For comparison, the initial speed (muzzle velocity) of the ball can be determined by shooting the ball horizontally off the table onto the floor and measuring the vertical and horizontal distances through which the ball travels. For a ball shot horizontally off a table with an initial speed, v_0, the horizontal distance, x, traveled by the ball is given by

$$x = v_0 t\ ,$$

where t is the time the ball is in the air. Air friction is assumed to be negligible. The vertical distance the ball drops in time t is given by

$$y = \frac{1}{2}gt^2\ .$$

The initial velocity of the ball can be determined by measuring x and y. The time of flight of the ball can be found using

$$t = \sqrt{\frac{2y}{g}}\ , \tag{10.5}$$

and then the muzzle velocity can be found using

$$v_0 = \frac{x}{t}\ . \tag{10.6}$$

Part I Determining the Initial Velocity of the Ball

For this investigation you will need the following equipment:

- Projectile launcher with ball
- Table clamp
- Meter stick
- Plumb bob
- White paper
- Carbon paper

Activity 1.1 Initial Velocity of the Ball

1. Clamp the projectile launcher to a sturdy table (near one end of the table).

2. Adjust the angle of the projectile launcher to zero degrees so the ball will be shot off horizontally, away from the table onto the floor.

3. Put the ball into the projectile launcher and cock it to an appropriate range position. Fire one shot to locate where the ball hits the floor. At this position, tape a piece of white paper to the floor. Place a piece of carbon paper (carbon-side down) on top of this paper and tape it down. When the ball hits the floor, it will leave a mark on the white paper.

4. Fire ten shots.

5. Measure the vertical distance from the bottom of the ball as it leaves the barrel (this position is marked on the side of the barrel) to the floor.

   Vertical distance, y =______ m

6. Use a plumb bob to find the point on the floor that is directly beneath the release point on the barrel. Measure the horizontal distance along the floor from the release point to the leading edge of the paper.

   Horizontal distance to paper edge = ______ m

7. Measure the distance to each of the ten points. It will be easier if you measure from the edge of the paper, and then add the horizontal distance to the paper edge that you just found. Record these distances in the following table. Also calculate the average distance.

Trial	Distance, x [m]
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average	

8. Using the vertical distance and eq. (7.5), calculate the time of flight.

9. Using the average horizontal distance, the time of flight, and eq. (7.6), calculate the initial velocity of the ball.

   $v_0 =$______ m/s

Activity 1.2 Estimating the Uncertainty

1. Examine the ten marks left by the ball on the piece of paper. You should notice that the ball didn't hit the exact same spot all ten times. Why?

2. Based on the spread of the ten marks, estimate the uncertainty in the total horizontal distance. Do you think this uncertainty will have a significant effect on your calculation of the initial velocity?

Part II Ballistic Pendulum

For this investigation you will need the following additional equipment:

- Projectile catcher accessory
- Scale

Activity 2.1 Conservation of Momentum in an Inelastic Collision

1. Find the masses of the ball and catcher.

   Mass of ball, $m_b =$______ g

   Mass of catcher, $m_c =$______ g

2. Suspend the ball catcher as a pendulum, as demonstrated by your lab instructor.

3. Clamp the suspended ball catcher directly in front of the muzzle. Attach a thread to the ball catcher and string it through the Velcro assembly on the base of the launcher.

4. Load the launcher. Fire a test shot to see how far out the thread is pulled. Pull a few centimeters of the thread back through the Velcro, leaving the rest of the thread slack between the launcher and the catcher. When the ball is shot into the pendulum again, the thread will become taut just before the catcher reaches its maximum height. This reduces the effect of friction on the thread. Record the distance between the table and the base of the pendulum.

   Vertical distance at rest = ______ m

5. Fire the ball into the pendulum five times. After each trial, measure the height, h, that the pendulum rose. To do this, subtract the starting vertical distance that you just measured from the new vertical distance when the string is taut. Pull the string back a few centimeters after each trial. Record your measurements and their average in the following table.

Trial	Height, h [m]
1	
2	
3	
4	
5	
Average	

6. Using the average h, and eq. (7.4), calculate the initial velocity of the ball.

   v_0 =______ m/s

7. You've now calculated the initial velocity, v_0, in two different ways. What is the percent difference between your two results?

   % difference = ______ %

8. What percentage of the kinetic energy is lost in the collision? Note that you'll need eq. (7.3) to calculate the final velocity, v, (which you need to find the final kinetic energy).

   KE_{final} =______ J KE_{initial} =______ J

   % difference = ______ %

9. What happened to the kinetic energy that was lost? Was conservation of energy violated? Explain.

10. How does the height, h, to which the pendulum swings change if the ball is bounced off the rubber bumper on the front of the catcher instead of being caught? Why? Make your prediction below.

11. Now try it, but be sure to move the catcher farther away from the launcher so the ball won't rebound into the launcher and damage it. What happened? Was your prediction accurate?

Lab 11

Periodic Motion

Pre-Lab: Periodic Motion

Name:________________________________ Section:______

1. What is periodic motion? Give three examples of systems that demonstrate periodic motion.

2. There is a minus-sign in the equation for Hooke's Law. Write down Hooke's Law and explain the physical meaning of the minus sign.

3. The symbols ω and f are both often used to mean "frequency", yet they have different meanings. What is the difference between ω and f, and how are they related to one another mathematically?

4. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

5. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Periodic Motion

Machines take me by surprise with great frequency.

Alan Turing

Objectives

- To explore the characteristics of periodic motion.
- To determine what relationships exist between period, frequency, and amplitude.

Overview

Periodic motion is motion that repeats itself. You can see the repetition in the position, velocity, or acceleration-time graphs. The length of time to go through one cycle and to begin to repeat the motion is called the *period*. The number of cycles in each second is called the *frequency*. The unit of frequency, cycles per second, is given the name *Hertz*.

Part I Motion of a Mass Hanging From a Spring

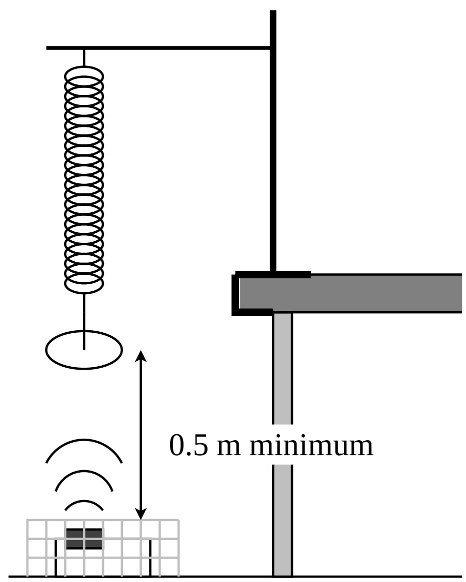
For this investigation you will need:

- Computer
- Motion detector with protective screen
- Lab stand
- Spring
- Weights
- Mass pan

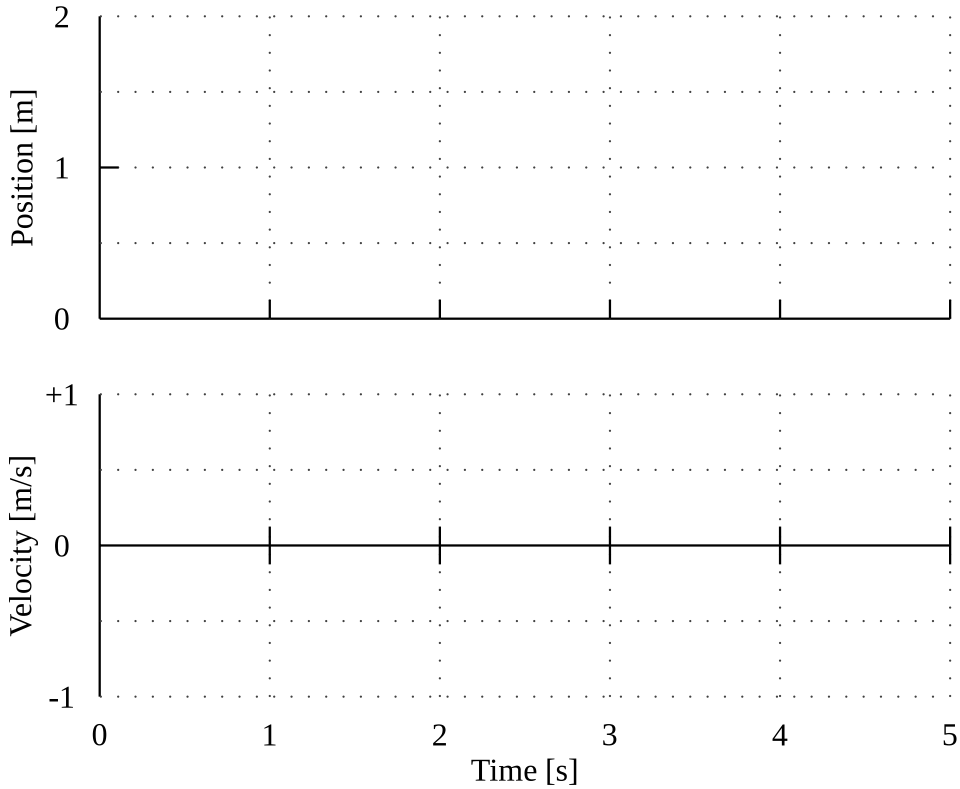
Activity 1.1 Periodic Motion of a Spring and Mass

In this activity you will examine the graphical display of the motion of a mass hanging from a spring.

1. Setup the experiment as shown below. The motion detector should be plugged into *Dig/Sonic 2*.



2. Open the program *Periodic_Motion_A1-1.exp*. The following graph should appear on the screen.



3. Hang a mass of 200 g from one of the springs (be careful to account for the mass of the mass pan). Push the mass up and let go. Adjust the height of the support so that the mass comes no closer than 0.5 m to the detector.

4. Make *distance*- and *velocity-time* graphs of the motion of the mass by clicking on *Start* to begin graphing. Be sure the detector sees the mass over its full range of motion and that there are no flat portions of your graph where the mass came too close to the detector. Sketch the result on the axes above.

5. Label the graphs above with:

   - "B" at the Beginning of a cycle
   - "E" at the End of the same cycle
   - "A" on each spot where the mass is moving Away from the detector with the greatest speed

- "T" on each spot where the mass is moving Toward the detector with the greatest speed
- "S" on each spot where the mass is Standing still
- "F" where the mass is Farthest from the detector
- "C" where the mass is Closest to the detector

Note that when an object returns to the same position, it does not necessarily mean that a cycle is ending. It must return to the same position, *and* the velocity and acceleration must also return to the same values in both magnitude and direction for this to be the start of a new cycle.

6. Describe the velocity graph and compare it to the distance graph. Do they appear to have the same period? Do their peaks occur at the same times? If not, how are the peaks related in time?

Activity 1.2 Period, Frequency, and Amplitude

1. Measure the period and frequency of the motion represented by the graphs above. Select the *x=?* button on the *Menu bar* to help you read the graph accurately. To determine the frequency and period more accurately, measure the total time over several cycles and divide by the number of cycles.

   Number of cycles counted:______ Time for these cycles:______ s

   Period: ______ s Frequency: ______ Hz

2. The midpoint of the motion is also the point where the mass will hang at rest. This position is called the *equilibrium position*. The *amplitude* of the motion is the maximum displacement from the equilibrium position. For ideal harmonic motion the amplitude will be constant in time. Is this the case for your motion? Why might the amplitude change with time?

3. Find the equilibrium position and the amplitude. First store your graphs by going to the *Data* selection on the *Menu bar* and select *Store Latest Run*. To find the equilibrium position of the mass, take a distance-time graph with the mass hanging at rest. Choose *x=?* to determine the equilibrium position.

   Equilibrium position: ______ m

4. Calculate the amplitude as the difference between the maximum displacement and the equilibrium position at the start of the motion.

   Maximum displacement: ______ m   Amplitude: ______ m

Part II Simple Harmonic Motion

In addition to the materials form the previous Part, you'll need:

- Two more springs
- Spreadsheet program (Excel)

Activity 2.1 The Period of S.H.M. and the Amplitude

1. What can you do to change the period in Simple Harmonic Motion (SHM) when the system consists of a mass and spring? Consider the possibilities: change the amplitude, the hanging mass, or the stiffness of the spring. Imagine changing one of these and leaving all else the same. What would you predict will be the effect on the period if you:

   a) Decrease the amplitude?

   b) Increase the mass?

   c) Make the spring stiffer?

2. If you start the SHM and measure the distance vs. time for a long enough time, you may find that the amplitude decreases with time. Adjust the mass that is on the spring until you get a significant decrease in amplitude in a reasonable amount of time.

3. Does the period depend on the amplitude?

Spring Restoring Force and SHM

1. Using *Hooke's Law* ($F = -kx$), measure the force constant of the spring that you've been using (we'll call this spring S1). Carefully measure the position of the mass when it is at rest with each of four different masses hanging from it. You can do this accurately by plotting a *displacement-time* graph with each mass in turn hanging from the spring at rest and using *x=?*. Be careful here. Is distance from the motion detector really x in *Hooke's Law*? Record the data below.

Spring S1 (Color: ______)

m [kg]	F [N]	Distance from Motion Detector [m]	x [m]
0	0		0

2. Plot a graph of force vs. displacement. Enter the data into a spreadsheet, plot it, and a add a trend line to find the slope. Show the graph to you lab instructor. How is the slope of this line related to the force constant of spring S1? Enter the force constant below (this force constant is often called the *spring constant*).

$k_1 =$______ N/m

3. Find the force constants for the two other springs, S2 and S3, using the same method as above.

Spring S2 (Color: ______)

m [kg]	F [N]	Distance from Motion Detector [m]	x [m]
0	0		0

$k_2 =$______ N/m

Spring S3 (Color: ______)

m [kg]	F [N]	Distance from Motion Detector [m]	x [m]
0	0		0

$k_3 =$______ N/m

Activity 2.2 The Force Constant and SHM

1. Return to using a mass of 300 g, which we'll now call M1. Measure the period, T, of the two other springs, S2 and S3. Recall that you've already used M1 with S1—if for some reason you haven't, do so now.

Combination	k [N/m]	T [s]
M1 and S1		
M1 and S2		
M1 and S3		

2. Does the period depend on the spring constant? Does it regularly increase or decrease as k is increased?

3. Determine the mathematical relationship between the period, T, and the spring constant, k, by plotting a graph of T vs. k. Is this a linear relationship? Also try plotting T^2 vs. $1/k$ and $1/T$ vs. k^2. Are any of these a linear relationship? Show your lab instructor the graph that you think is closest to linear.

4. What is the mathematical relationship between T and k, including the constants? Note:
$$\omega = \sqrt{\frac{k}{m}}\,, \qquad T = \frac{2\pi}{\omega}\,.$$

5. Does your mathematical result agree with the relationship that you found graphically?

Activity 2.3 The Mass and SHM

1. Use spring S1. Measure the periods using two other masses, M2 and M3.

Combination	m [kg]	T [s]
M1 and S1		
M2 and S1		
M3 and S1		

2. Does the period depend on the mass? Does it regularly increase or decrease as m is increased?

3. Determine the mathematical relationship between the period, T, and the mass, m, by plotting graphs of T vs. m, T^2 vs. m, and T vs. m^2. Which of these relationships is linear? Show that graph to your lab instructor.

4. What is the mathematical relationship between T and m, including the constants?

5. Does your mathematical result agree with the relationship that you found graphically?

Lab 12

Temperature and Heat Transfer

Pre-Lab: Temperature and Heat Transfer

Name:______________________________ Section:______

1. If two objects, one at 5°C and the other at 100°C, are placed in thermal contact, what other information do you need to calculate their final temperature? Assume no heat is lost to the environment.

2. What would the final temperature be if 16 g of solid aluminum at 5°C were put in thermal contact with a cup containing 32 g of water at 35°C? Note that you'll need to look up some information in your textbook to do this problem. Assume no heat is lost to the environment.

3. Why is water often used to cool industrial equipment? Why not just use air?

4. Briefly summarize the procedures you will follow in this lab. Write one or two sentences for each activity.

5. List any part (or parts) of the lab that you think may suffer from non-trivial experimental error, or may otherwise cause you trouble. How might this affect your results?

Temperature and Heat Transfer

It doesn't make a difference what temperature a room is, it's always room temperature.

Steven Wright

Objectives

- To acquire an operational definition of temperature.
- To understand the connection between temperature and thermal equilibrium.

Overview

With this lab we begin the study of thermodynamics, a new and profoundly different way of studying physical phenomena. Much of the physics studied in previous labs involved motions that we could see while many of the changes we will encounter in thermodynamics will not be visible without the help of indirect measuring instruments such as thermometers.

In general, the measurement of temperature depends on some characteristic of material in the thermometer changing as it is heated or cooled. Thus, the length of a metal rod, the height of a column of mercury or the volume of a gas under pressure can serve as means of measuring temperature. It is also possible to use electronic devices to measure temperature.

In order to use an electronic sensor, it must be calibrated against the glass bulb thermometer or some other known standard. The electronic sensor that you will be using is a device whose voltage is a function of the temperature. The LabPro Software will read the voltage and give the temperature, but it should still be checked against a glass bulb thermometer.

Another important concept is that of *specific heat*. The heat (energy), Q, that an object absorbs or loses is proportional to a quantity called the specific heat, c, as well as the temperature, T, and its mass, m:

$$Q = mcT\ .$$

The specific heat of water is 4190 J/kg/K.

Part I Measuring Temperature

You will be working with boiling water in this lab. Be careful!

For this part of the lab, you'll need:

- Electronic temperature sensor
- Computer
- Hot pot (to boil water)
- Water
- Ice
- Insulated cups

Activity 1.1 Calibrating a Temperature Scale

To test the accuracy of the temperature sensors you'll measure things with known temperatures. To this end, you'll exploit the fact the water freezes at 0°C and boils at 100°C (with slight variations based on air pressure and purity).

1. Connect your temperature sensor to Channel 1 of the interface and place about 1 cm of the tip of the sensor into a container which has a mixture of ice and water in it. Load experiment *Steel Probes* (or *Steel Temp*) and measure the temperature as a function of time until the reading has become more or less constant. You might also want to note the time that it takes for the reading to become constant.

   Temperature = ______ °C   Time = ______ s

2. Now repeat the measurement for water boiling under atmospheric pressure. Use the hot pot to boil some water. Note: You will probably want to place the sensor into the water only after it has started boiling gently.

   Temperature = ______ °C   Time = ______ s

3. Now you need to establish a temperature scale. You can do this by defining the temperature of ice water and boiling water. If you are Andy Celsius you might call the lower temperature zero degrees and the higher temperature 100 degrees, while if you are Gabe Fahrenheit you might call the lower temperature 32 degrees and the higher one 212 degrees. Let's assume that you like the Celsius scale. Now measure "room temperature" with both your temperature sensor and seperate glass bulb thermometer.

   Room Temperature (sensor) = ______ °C

   Room Temperature (bulb) = ______ °C

4. Compare your room temperature to the temperature measured by a more conventional glass bulb thermometer. Is your sensor accurate, or is it off by a certain amount? If it is off, how much is it off by?

Activity 1.2 Time Delays

There are a couple of things you should know about temperature sensing in order to measure temperature more accurately.

1. When a nurse pops a room temperature thermometer in your mouth to see if you have a fever, can the temperature be determined immediately? Why not?

2. Suppose you want to measure room temperature with a thermometer that has been in ice water. Which do you predict would cause more time delay, measuring room temperature water or room temperature air? Explain the reason for your prediction. Try to verify your prediction by recording the thermal equilibrium times of an electronic temperature sensor as the voltage changes over time when it is transferred from ice water to room air and ice water to room temperature water.

   Ice water to room air: $\Delta t =$______ s

   Ice water to room temp water:$\Delta t =$______ s

3. On the basis of these observations what should you watch out for in making temperature measurements?

Part II Thermal Equilibrium

Are objects lying around a room really at the same temperature? To explore this question of thermal equilibrium you can use the following additional materials:

- Metal block
- Wood block
- Styrofoam block

Activity 2.1 Relative Temperatures

1. Feel the wood, metal, and Styrofoam. Predict which one actually has the highest temperature and the lowest temperature, and compare that to how they feel.

2. Now measure the temperature of the three objects and record your measurements in the following table.

Material	Temperature [°C]
Metal	
Wood	
Styrofoam	

3. Did your observation agree with your prediction? Is your sense of touch an accurate predictor of relative temperatures?

4. According to other observations you have made in this session, should the temperatures of three different materials sitting around in the same room be the same or different?

5. On the basis of previous observations, you should be able to explain the reason why some objects feel colder than others. Hint: Is the temperature of your hand different than the room temperature? If so, what is happening when you touch an object which is at room temperature?

Part III Temperature Changes and Interactions

Does Temperature Tell the Whole Story? We know that when a hotter substance comes into thermal contact with a cooler one the temperatures of the two substances change. Do the initial temperatures alone allow us to predict the final temperature of the system after the two substances have interacted with each other? Suppose you have two liquids of masses $m_1$and m_2 in thermal contact inside a fairly well-insulated container. You will be asked to make some predictions and test them with some measurements. For this activity you will need:

- Two electronic temperature sensors
- Computer
- Insulated cup
- Balloon

- Hot pot
- Ice
- Water
- Graduated cylinder

Activity 3.1 Predicting Temperature Changes

1. If you were to place two *equal masses* of the *same type* of liquid having different temperatures in thermal contact how would you determine the final temperature? For example, suppose $m_1 = m_2 = 40$ g while $T_1 = 15°$C and $T_2 = 45°$C . What would you expect to happen to the temperature of each of the liquids after a while due to thermal contact between them? Note: Assume that the liquids are inside an insulated container so no interaction takes place with the room. Show your work.

2. If you were to place two *different masses* of the *same type* of liquid having different temperatures in thermal contact how would you determine the final temperature? For example suppose $m_1 = 15$ g and $m_2 = 45$ g while $T_1 = 15°$C and $T_2 = 45°$C. What would you expect to happen to the temperature of each of the liquids after a while due to thermal contact between them?

3. On the basis of what you already know what do you think is taking place when the two liquids come into thermal contact? Can you describe a possible mechanism for any interactions you might predict? Do you think it's possible on the basis of knowing just the temperatures, but not the masses, of the two liquids in the containers to predict the final temperatures of the two liquids after they have been in contact?

4. Test your prediction in Step 2. This can be done by placing the appropriate amount of water (45 g at 45°C) into the insulated cup and placing the cooler water (15 g at 15°C) into the balloon. Note that it will be hard to get the temperatures exactly right, so just get as close as you can. Connect the second temperature probe to Channel 2. Place a temperature sensor into each water sample and wait about 15 seconds so that the sensor can adjust to the temperature. Place the balloon with its sensor into the cup with its sensor, making sure that the outer sensor doesn't touch the balloon. Monitor the temperatures on a real time graph for about 300 seconds. Briefly describe your results. Was your prediction accurate?

5. Is there any evidence of the liquids mixing together or exchanging matter

during the thermal interaction? Is there any visible exchange of matter? Is an exchange of matter required during a thermal interaction?

6. If your observations did not agree with your predictions, what factors might have contributed to the difference? Hint: Is the system made up of two water samples only? The calculated temperature was probably around 5 degrees higher than the observed one.

Comment:
Inevitably, parts of any thermally isolated (i.e. insulated) system having different temperatures will interact until the entire system is at the same temperature. This is a mysterious process, because the interactions that cause temperature changes in two parts of a system until thermal equilibrium is reached do not seem to be exchanges of matter. You should have noticed from your experiments and those of your classmates that the relative masses of the parts of your thermally isolated system affect the value of the final equilibrium temperature. Thus, the interaction between two parts of a system cannot be explained as a simple temperature exchange. We need to create a new concept to help us understand heating and cooling processes. Scientists have invented the term *heat* in this context.
The use of the noun “heat” is misleading, since using this term to explain temperature changes implies the exchange of a substance between two parts of a system. The word “heat” is actually a sloppy shorthand for an interaction process which leads to temperature changes.

Appendix ***A***

Spreadsheet Tutorial

These notes are provided in case you are not familiar with spreadsheet use. A spreadsheet can be a very powerful tool for modeling a physical system. In this tutorial, we'll explore some of the more useful features of *Excel* by setting up a simple problem. Specifically, we'll try to find the values of x_0, v_0, and a in the equation

$$x = x_0 + v_0 t + \frac{1}{2} a t^2 \ , \tag{A.1}$$

when we already have a list of (x,t) pairs (see columns A and B of Fig. A.1). If at any point you need more detailed information on a particular topic, you can look under the *Help* menu in the spreadsheet itself.

In a spreadsheet a *cell* is denoted by the column letter and row number. The first cell in the upper left-hand corner would be A1; the one below it A2, etc. The *active cell* is high-lighted by a border, and you can move from cell to cell by moving the mouse cursor to the new cell and clicking on it, or you can use the arrow keys on the keyboard. At this time, you should open an *Excel* spreadsheet by double-clicking on its icon, so that you can follow along.

As discussed above, cells are referenced using a notation such as B2, and this is called a *relative reference*. Thus, if the active cell is C2 and a formula attached to that cell refers to A2—the cell two columns to the left of column C and in the same row as the active cell—then when the formula is copied to C3, the formula in C3 will update to reference cell A3 instead of A2. This is convenient if you want to perform the same operation on a list of data.

In contrast, an *absolute reference* is written with dollar signs, such as \$F\$2. When \$F\$2 is referenced in a formula, the reference will not change when the

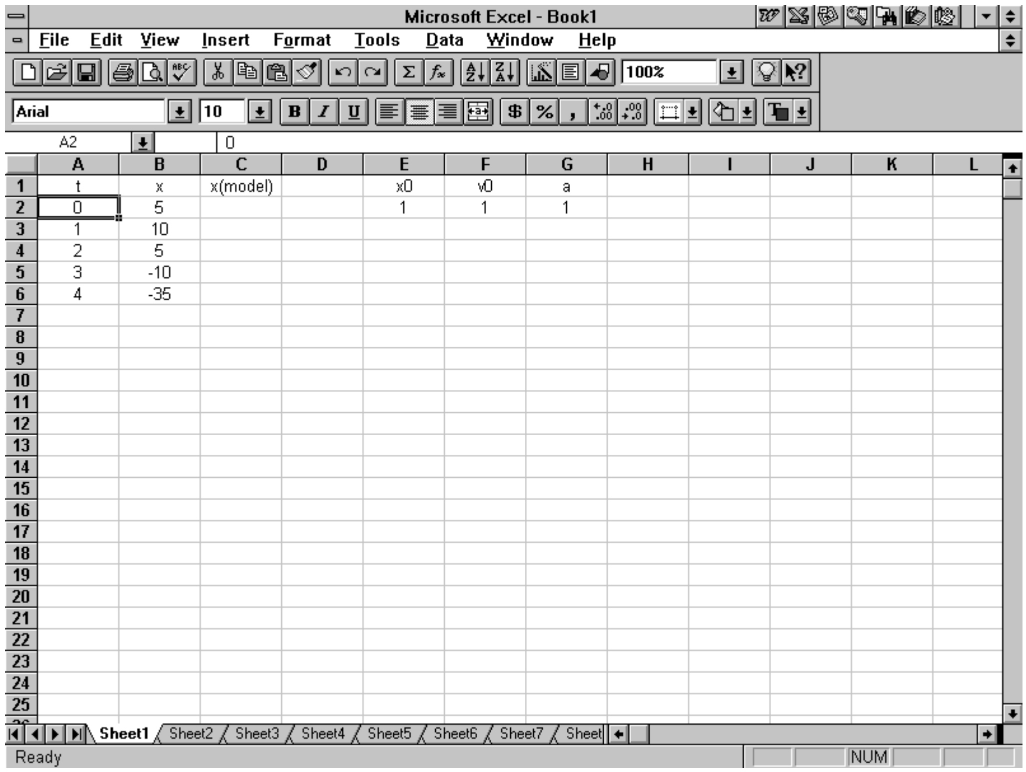


Figure A.1: A sample page from a spreadsheet with the columns labeled and some data listed in columns A and B.

formula is copied to other cells. This is useful if you want a cell to contain a constant or parameter. We'll use both relative and absolute references in this tutorial.

In setting up a model for the data in this example, we will model the x values as a function of t.

1. Using your spreadsheet, move the active cell to A1 and type in t and hit *Enter*. Now move the active cell to B1 and type in x and hit *Enter*. Continue for the other column headings in row 1 as shown in Fig. A.1. Here x0, v0, and a are adjustable parameters. Since we believe that the data is related to the position of an object along the x-axis which can be described mathematically by eq. (A.1), we will set up our model accordingly.

2. Move the active cell to E2 and enter a trial value for the parameter whose

label (or symbol) is in E1. Continue for F2, and, finally G2. (A good set of beginning values is usually the simplest, so just enter 1 for each of the values.)

3. Now type in the values in the spreadsheet above for the times in column A and the distances in column B.

4. Move the active cell to column C and row 2 (C2). Type in the *formula* which we believe describes the motion. First type in an = sign, this tells *Excel* that you will be entering a formula, rather than just a label or number. The first term after the = corresponds to x0 and is the trial value in cell E2. (Here we have to use an absolute reference, so you should now have =$E$2.) The second term is added to this, so type in a + sign. Now type in the product of the trial value in cell F2 (under the v0 label) and the time which is in cell A2. Note that * is used for multiplication. You should have typed in $F$2*A2. The last term is the product of 0.5 times the trial value in cell G2 times the time in A2 squared (A2^2). The following is now in the active cell C2:

   = $E$2+$F$2*A2+.5*$G$2*A2^2

   Hit *Enter*.

5. Now you want to copy this formula down to the rest of the rows in column C. You can use the *Copy* and *Paste* commands in the *Edit* menu, or you can move the cursor to the lower right hand corner of the active cell (C2) until a black cross appears. Click, and drag the cell down the necessary number of rows in order to copy the formula to the other cells.

6. In order to see how changing the parameters will affect the model, it is usually easier to have a graphical representation of the data and model. Click and drag to highlight the first three columns to select the data to plot.

7. Now click on the *graph* button on the top button-bar menu and follow the prompts to complete the chart. When given the option of which type of graph to plot, choose an *xy scatter*. Try to place the graph so that you can see the values in E2, F2, and G2 as well as the graph.

8. Once the graph is in place, move the cursor to one of the parameter cells (E2, F2, G2) and enter trial values until the model and the data agree. Notice how the numbers in column C and the graph update automatically.

Notes: