PHYSICS LABORATORY MANUAL

PHY180

Academic Session 2015 – 2016

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HEALTH AND SAFETY IN THE LABORATORY

1. LEAD OBJECTS

Lead can be absorbed into your body through your skin or your mouth, and can produce brain damage. In order to minimize your exposure to lead in the laboratory you should wear gloves when handling lead objects (gloves are available at the **R**esource **C**entre in room 126), and wash your hands after completion of the experiment; do not handle any food while working with lead. However, by far the main hazard of lead shielding is its intrinsic weight. Hence, in order to prevent foot or hand injuries, be careful when moving heavy lead objects around.

2. ELECTRICITY

The lab equipment is set up so that exposed wires carry low harmless voltages. However, if you suspect that any terminals carry dangerously high voltages (over 60 volts), check to ascertain their safety, and be careful not to touch these terminals. When handling potentially hazardous electrical equipment, work with one hand in your pocket or behind your back, and stand on an insulated surface so as to not provide the electricity a path to pass through your body. In the event of any accident in the laboratory, notify a lab demonstrator or a lab technician immediately.

3. STROBOSCOPES

A small fraction of the population is susceptible to epileptic seizures if they view a "strobe" light that is flashing at 10-20 Hz. Students with a history of epilepsy should refrain from using a stroboscope at those frequencies.

4. MAGNETS

The new high field magnets pose a danger to pacemakers and other electrical devices. If you suspect that you may be vulnerable in this area, make sure that you talk to the laboratory coordinator before signing out any of these magnets. Also, credit cards or other cards with magnetic stripes, can be rendered unreadable by a too close approach to these very high field magnets.

GENERAL INFORMATION

I. INTRODUCTION

Welcome to the first year physics laboratory. We hope that you will have an enjoyable and rich learning experience in this laboratory. First, a statement about the lab's philosophy. The study of Experimental Physics differs from that of theoretical physics in several ways. The immensely complex physical reality that surrounds us is often described in terms of ideal models of a simplified universe. The experiments in this laboratory will enable you to grapple with many of the complicated and infuriating aspects of the real world and begin to discern the connection between the constructs, which you are developing in your theoretical studies, and the rich and varied environment, which they attempt imperfectly to describe. The main goal of the lab is to give you an appreciation of the power of experimental science in the development of our knowledge about the physical world. The lab is designed to help you develop skills to:

- **design and appreciate the design of intelligent experiments**
- **solve any practical problem**
- **keep complete records**
- **manipulate equipment and measuring instruments with grace**
- **distinguish between the essential and the non-essential**
- **analyze data efficiently and accurately**
- **display data in tabular and graphical form**
- **estimate the uncertainties in experimental results**
- **ask the right questions and design further experiments to answer them.**

The Lab is **NOT** designed to:

- **only illustrate lecture material**. While we have designed the lab to allow you to pursue some of the topics being covered in first year lectures, this is **not** a demonstration lab.

- **train you to follow instructions.** Some undergraduate labs provide step-by-step directions for performing standard experiments. Within a fairly well defined context, you will be expected to create your own direction and find your own path of exploration. In short, we are often more interested in your ability to develop the skills to make a physical measurement of significance than in the result itself and more interested in the method of approach rather than getting the "right" answer.

It is recommend that you submit your lab reports in electronic format. This means that you will put all data, tables and diagrams into a MS Word document and submit this file electronically by the assigned deadline. Your instructor/TA will make notes and assign marks in your electronic lab report. You can choose to submit a hardcopy, hand-written report using the old-fashioned lab notebook. Both formats will be considered identically valid.

II. GETTING STARTED

Check the laboratory web site for the date of your first laboratory session. The laboratory Course Homepage is reached from:

www.physics.utoronto.ca/students/undergraduate-courses/course-homepages/phy180h1lab

Check this web page for a link to Capstone exercise that we recommend you to perform before your scheduled lab session. This exercise give you an idea of software you will be using.
The web site contains information that complements information on the University of Toronto Portal (your PRA section of the Blackboard). Booking experiments of free choice is not available from the Portal. We recommend you to use both web facilities and study their contents thoroughly. You have an opportunity to easily switch from one web site to the other.

When you come to your first laboratory session, you will need:

- Your personal USB flash drive for saving experiment data and create electronic lab reports
- Electronic calculator
- Good clear plastic ruler of at least 30 centimetres in length, pens and pencils. You do not need a lab coat or goggles!
- You may use **a special Physics Laboratory Notebook in white coversheet** that contains some useful information on error calculations and physical constants and units. You can either record all your experimental work and write your lab report in this notebook and submit for marking, or just use it for your own notes or sketches if your lab report is prepared and submitted electronically. The White Notebook is available in the U of T Bookstore (214 College Street, Koffler Center). The White Notebook is optional.

III. STRUCTURE OF THE LABORATORY

Each **lab section** of the class has a three-hour lab session every second week. Each lab section is divided into **lab groups** (with numbers like 3LD, 4PT, 5CW etc.) with about 10 - 14 students in a group. Each group has a Lab Demonstrator – a Teaching Assistant, who provides supervision, guidance, organization, marking and assistance throughout the term. Although a lab demonstrator has a specific group responsibility, all of them are available, along with the Lab Coordinator, to answer questions from any student. You will meet your Demonstrator on your first lab day.

You will work with a lab partner who must be in the same lab section and group.

Important! Learn the name, the office location and the telephone number of your Lab Demonstrator. Enter the contact information of your lab demonstrator and lab partner, your lab section number and group ID into your file with the first lab report and save this file until the end of the term, or Print your Demonstrator's name, your lab section and group number on the front page of your lab notebook. The Course Homepage will list all Demonstrators with their personal information under the link “Staff”. You can also find the contact information of all lab demonstrators in your lab section on the U of T Portal, or the Blackboard, in the Content area (“Contact”).

For students who choose the laboratory notebook for submitting the lab reports, it will serve as an ongoing record of **ALL** data, **ALL** “rough work”, and an account (perhaps in note form) of what you are actually doing, **written as you actually do it** (as opposed to recollections made after the fact). Detailed essays on your procedure are **not** required.

IV. REQUIREMENTS

You are required to attend six lab sessions in the Fall Term. If you miss a lab for any reason such as illness, you must make up the lab at another time agreed upon with your Demonstrator. You will receive a mark of zero for each lab that you miss and do not make up.

You are required to finish 6 “weights” of experiments. The “one weight” experiments are designed so that their data-taking stage can be completed within one three-hour period. However, this will be true **only** if you have spent some time beforehand in preparation and fully understand the purpose and method of approach of the experiment you are about to perform. We also expect that you may have to do some of the final analysis outside the lab hours. The “two weight” experiments take twice as long and count as two “one weight” experiments. Before coming to the lab session, read instructions in this Manual and experiment handout posted to the Blackboard (BB) and try to understand physics being studied. Some experiments have Preparatory Questions that will be posted to the BB as a short test with a set of Multiple Choice questions. The system will assign a mark for Preparatory Questions, which will be included by your Lab Demonstrator into the Experiment Mark.

Compulsory (=Required) Experiments in Classical Mechanics
These four experiments are performed by all students of the class. The instruments you will be using are connected via an interface to a PC for recording and analysing your data. Each experiment counts for one weight.

Experiments of Free Choice
For the last two lab periods you will select from a list of experiments in Classical Mechanics posted on the course Homepage

http://www.physics.utoronto.ca/students/undergraduate-courses/course-homepages/phy180h1lab

(link “Experiments”).

All free choice experiments must be booked ahead of time using the on-line booking procedure. The on-line booking becomes accessible during the last week of October on the same web page “Experiments” by clicking on the active link Book an Experiment at the bottom of the page with the list of optional experiments.

Your login to access the on-line booking is your student number - i.e. 1005165394.Your password is your "official" last name, as known to ROSI (case-sensitive, like Smith).

Because some of challenging experiments exist in just one or two setups, it is important to be the first in your lab section to book an experiment of your choice. Together with your lab partner discuss your preferences in advance and prepare at least one more experiment as an option.

V. MARKING SCHEME

The laboratory is a part of the course PHY180H1F. Your lab related marks contribute 25% to the PHY180 course mark, weighted equally among the six labs you do in the semester.

You will find all your current lab marks on the Blackboard (BB) in your PRA section. The lab marks are entered into the BB database by your Lab Demonstrator. If the mark for an experiment is not entered for more than two weeks after you get back your graded lab report, contact the Laboratory Coordinator in person or via e-mail.

Your Lab Demonstrator will mark the experiment after the session outside the laboratory. Feel free to discuss your mark with your Lab Demonstrator in the next laboratory session.

Some of your experiments - to be decided on by the Lab Coordinator- may be marked by Lab Demonstrators of the other groups. This will allow for some standardization of marks between lab demonstrators and give you an opportunity of getting some different feedback on your work.

Criteria for the Experiment Mark
This mark will be mainly based on the work you have recorded either in electronic report or in your notebook. Your Demonstrator will be looking at your performance in the following categories:

- adequate and careful pre-experiment preparation (for some of experiments, for example, this will be evidenced by correct answers to the *Preparatory Questions;* in others, you may be asked to show evidence of having mastered background material etc.)
- arriving to the session on time
- creativity in designing experiments
- care in handling of equipment
- good statement of experimental procedures
- good overall organization of your records
- clarity of description
- appropriately wide range of data displayed as it was taken, in well-labelled tables, graphs and diagrams used appropriately and in reasonable quantity
- correct units used throughout
- correct error calculation and data self-consistent with all errors indicated
- brief but complete discussion of results
- indications of limitations of the experimental method, with comments on possible extensions
- summary of experiment results and conclusions
- your ability to cooperate efficiently with your lab partner

Your final Experiment Mark will be calculated at the end of the term as a sum of marks, assigned for all experiments.

VI. UNCERTAINTY AND SIGNIFICANT FIGURE

Analysis of experimental uncertainty is one of the most important things that you will learn in the first year laboratory. Consult APPENDIX I. SIMPLIFIED UNCERTAINTY ANALYSIS for a brief introduction of error analysis and uncertainty. You can find a more complete treatment on data analysis in the book:

P.R. Bevington and D.K. Robinson, *Data Reduction and Error Analysis for Physical Sciences* (3rd ed., MGH, 2003). The book is available in the U of T Bookstore and in the Department of Physics Library (2nd floor of Burton Tower).

Usually we keep only one significant figure for the error, which determines the significant figure of the result by keeping it to the same decimal place as the error.

Example 1
Using a vernier caliper, you have 10 times repeated measurements of the diameter d of a cylinder. You estimate that the reading error in reading the vernier is ±0.005 centimetres. You calculate that the statistical uncertainty of your sample of measurements is 0.001 centimeters. What is the error in centimetres in each individual measurement of the diameter d?

The correct answer to this question is **0.005** centimetres.
The question involves the topic: "Choosing between the standard deviation and the reading error".

Example 2
You have one measurement of the length of a vertical path of a freely falling object with the result:

$$H = (2848.0 \pm 0.5)\ mm$$

The time of the free fall of the object measured with electronic stop-watch gives:

$$t = 0.755 \pm 0.005\ s$$

Using the formula for the uniformly accelerated motion with zero initial velocity, calculate the acceleration due to gravity with its error obtained in your experiment.

The displacement of the free falling object can be written as

$$\mathrm{H} = \frac{1}{2} g t^2,$$

so the acceleration due to gravity is

$$g = \frac{2H}{t^2} = 9.99254\ \ldots,$$

and its error

$$\Delta g = g \cdot \sqrt{\left(\frac{\Delta H}{\mathrm{H}}\right)^2 + \left(\frac{\Delta t \cdot 2t}{t^2}\right)^2} \approx 0.1.$$

Keeping the result of g to the same digit as the error, the final answer is $g = 10.0 \pm 0.1\mathrm{m/s^2}$.

VII. RECORDING YOUR EXPERIMENT

i.) Your lab report for a compulsory experiment

Two formats are accepted for your lab report: 1 - electronic document in MS Word or 2 - a write-up in a white lab notebook. Each compulsory experiment has a folder in the common folder "Compulsory experiments" in the Course Documents on the BB (PRA section). The folder of each experiment contains a handout in MS Word and a template to be filled with results of measurements, calculations, discussion and summary.

If you decide to submit your lab report in electronic format, be sure that you have your USB flash drive at every lab session to keep records and save them until the end of the term. Before the upcoming lab session, submit answers to Preparatory Questions (PQs) for your new experiment if required. We recommend saving the test with answers to PQs to your USB drive. Your Lab Demonstrator will check your mark for PQs on the BB prior to the beginning of the lab session. This message will confirm that you have spent some time for the experiment preparation. If the PQs are not answered before the lab session, you will get lower mark for the experiment.

If you choose the paper write-up to be submitted for marking, everything you do in the lab should be recorded in your lab notebook *while you are doing the experiment*. Your lab report should begin with answers to PQs if required for a particular experiment. Your Lab Demonstrator will check existence of the answers at the very beginning of the session. The lab notebook should contain **all** your rough calculations or preliminary measurements, full details of any error calculations, any comments, records of successes or failures, etc. Enter the title of the experiments you do in the *List of Experiments*, along with starting and completion dates. There is no point in copying information that is already in the handout. Nor is there any point in writing a detailed essay on your procedure; note form is quite sufficient, as long as it is complete and comprehensible to your Lab Demonstrator. Because the lab book is a complete record, taken as the experiment is being done, it will not necessarily be overly neat. Your write-up cannot exceed 10 pages including all diagrams, tables, etc. If necessary, you can print out a graph or a table or a figure and securely stick in into the notebook **Penalties will be imposed for surplus of graphs as not all of them are cited in the text.** If you use graph paper at the end of the notebook or have computer drawn graphs, stick them in neatly beside your description of the experiment. It is not a requirement but a good practice to keep the record of the experiment on facing pages, and any rough work, doodles or scribbles on the back pages (labelled "*Rough Work*").

ii.)Format

Many students find it convenient to organize their work under section headings, such as *Title, Introduction, Purpose, Theory, Apparatus, Procedure, Results, Conclusions*, etc.; however such organization is most effective if it is modified as required for each experiment. For managing your time successfully in the 1st year labs, we do not require this format for your report.

Most workers doing research in experimental science find that a diary format works best, which means that the record is written in the order in which a procedure, calculation or inspiration actually occurred. The present tense, active voice is often used in the recording of an experiment.

You should also NOT spend much time "tidying up" your notebook, or "rewriting history"; your time is too valuable, and vitiates the function of the notebook.

Electronic template will suggest you a format for this kind of the report submission. To open a new Word document, find an icon on the desktop, double click and open the Blank Document.

iii.) Printing in the lab

The first four compulsory experiments and the majority of experiments of free choice are performed in MP 126 and are associated with utilizing the Capstone software, which permits you to organize data in tables and graphs. If you need to print out the data, you should use a default printer in the same room (MP 126) for free. In the lab notebook, the Lab Demonstrator will expect from you only the graphs that are used or referred to in your calculations and/or in the text of the write-up. Too many graphs may sometimes reduce your experiment mark, as they show that you have not perfectly understood the objective of the experiment.

The printer in MP 126 is locked during the time not scheduled for laboratory work. You still have an opportunity of printing materials in the MP building out of the labs time; a printer in MP 257 is always available but is not free of charge.

iv.) The truth, the whole truth and nothing but the truth.

Record the actual values measured and the actual ways in which the instruments responded even though those values and responses are not what your preconceived ideas or the theory would have led you to expect. Often in experimental science it has been the anomalous results and unexpected phenomena that have later proved to be of the most value. It is important that at this early stage in your scientific career you develop the habits of objectively and of truthfully recording your observations and measurements.

Your record should be complete. This means that, five years later, anyone should be able to read your notes and know exactly what was done, when it was done and how it was done (what equipment and techniques were used, the details of any calculations). In addition you should include, where appropriate, what you thought about the individual measurements; "poor data," "sticky meter," etc. Your description of the equipment should include the manufacturer, model number and the serial number of every piece if possible (so that you can return to the very same equipment later if necessary).

Plagiarism (that is, representing other people's work as your own) and invention (that is, reporting imaginary data) are serious academic offences. Plagiarism or invention can result in disciplinary measures that are referred to the Dean of your faculty.

Laboratory work done without your Demonstrator's knowledge will not be marked. If you use other people's work in your lab report, you must cite that work properly (including the author, title, journal, date, etc.). It is not plagiarism if you do proper citations.)

A relevant question when two (or three) lab partners working together to write up their work is: "how independent can each person's report be?" It is acceptable to fully discuss the problems and interpretations of the experiment together (by doing so you learn from each other) and to have similar data and graphs. But it is not acceptable to have the same analysis, introduction, discussion, conclusion etc., which should be done independently.

v.) Strategies for Taking and Recording Data

When you take data, you gain both speed and accuracy if you approach the process systematically. A methodology appropriate to many experiments is as follows:

- **Identify the variables** you are measuring and the calculations you have to do on these variables, and make a table in your electronic document or a notebook with appropriate columns.
- **Identify the range of values** of these variables by considering what you want to measure, and by doing a preliminary run of the experiment from which can tell you how your apparatus behaves and what numbers to expect.
- **Obtain your data** (with error estimates) entering these in a table, and perform appropriate calculations on each data point if necessary. If you are using Capstone, you can plot the data on a graph as you are collecting data.

- **Check your results** for consistency and completeness. Once you plot the data on a graph you can check if there are questionable or inconsistent points (from abnormality of the equipment, for example). You can also check if there are regions of the data that are not sufficiently investigated and take additional measurements if necessary.
- **Calculate errors** for all measured quantities and their functions. You need to do error analysis for EVERY lab. Get feedback from your Demonstrator early on.
- **Interpret** your results and their uncertainties. Identify the sources of uncertainties.

VIII. WHAT TO EXPECT FROM YOUR LAB DEMONSTRATOR

Your Demonstrator should be the first port of call for all your questions about the lab. You should look on your Demonstrator as a supporter in all aspects of your learning in the lab. If there are any concerns about the way your demonstrator teaches in the lab, you can come and talk to the Lab Coordinator. Any comments you make will be kept confidential and we will make all possible efforts to ensure that your concerns are addressed.

i.) Time Keeping. You can expect that your Demonstrator is in the lab for the full duration of the lab. You may ask another Demonstrator or the Lab Coordinator for assistance if your demonstrator is busy with other students. Be proactive!

ii.) Marking. If you submit your report on time, your demonstrator will have your report marked before your next lab, so you will have a chance to get the feedback and improve in your next lab. You can expect comments to your report explaining where and how you could improve your work. All Lab Demonstrators follow same Marking Scheme and are trained identically.

iii.) Questions. Your Demonstrator may not answer every question directly. Instead, they are encouraged to guide you through and help you find the answer yourself. It is possible that sometimes your demonstrator may not even know the answer to some of your tough questions. In this case, you are encouraged to discuss with your Demonstrator and learn his/her approach of dealing with such questions and it is often the best time to learn the most from your Demonstrator.

iv.) Availability. Your Demonstrator is mostly only available during the lab hours. Occasionally you can email or make appointment with your Demonstrator outside of the lab hours if you have some questions about the lab or report. Make sure you record your Demonstrator’s contact information such as e-mail address, office and phone numbers.

IX. Saving Files

To save information and files relevant to the labs, use the portal option “Content” in the upper right corner of your Blackboard personal page. Button “Content” opens “Content Collection: My Content“. For the first time use, with the button “Folder +” add a folder which will contain all your experiment data. The capacity of the Content Collection is 50.00 MB.

On the laboratory computer we strongly recommend to save your files individually using your own USB flash drive. Two lab partners can plug in two USB drives and save same experiment data simultaneously. Any computer folder like *My Documents* is deleted daily as a part of rebooting the lab computers.

X. Resource Centre

The Resource Centre (RC) stores equipment and supplies for the experiments. Depends on which experiment you are doing, you may need to sign out equipment/supplies from the RC in MP 126 with your student ID. Some important handbooks and the course text book may also be available in the RC.

There is usually at least one technical expert in the Resource Centre that is available for students and lab demonstrators in case of equipment issues such as problems with computers, software, interfaces, malfunctioning sensors etc. You or your demonstrator may ask the technician in the RC for help for any technical issues with the experiment.

COMPULSORY EXPERIMENTS IN CLASSICAL MECHANICS

Experiments concentrate on Classical Mechanics, a topic you are studying in lectures. The experiments are designed to introduce you to some of the important techniques of experimentation and data analysis. All setups are assembled with PASCO sensors for data acquisition.

Compulsory experiments can be scheduled according to one of the two possible patterns:

$$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \qquad \text{or} \qquad 2 \rightarrow 1 \rightarrow 4 \rightarrow 3.$$

Check “My Grades” on the Blackboard to identify your first experiment (1 or 2).

The experiments are numbered and described in the following sections of this Manual:

1. **The Acceleration Due to Gravity**
2. **Newton’s Third Law**
3. **Dynamics of Rotational Motion**
4. **Simple Harmonic Motion**

The experiments are described here without details on a specific way of submission of your lab report: electronic document or a notebook. The details are in handouts on the BB. If an experiment has Preparatory Questions, answer them in the pre-lab test posted to the BB.

Experiment 1. The Acceleration Due to Gravity

Preparatory Questions

1. An object is launched up a frictionless plane inclined at an angle of θ to the horizontal. Make predictions about:
   a) the graphs of position, velocity and acceleration versus time (sketch these).
   b) the acceleration of the cart just after it is launched.
   c) the acceleration of the cart at its highest point.
   d) the speed of the cart when it returns to the point of launch.
2. Use your calculator to calculate the % difference between θ, sinθ and tanθ for θ = 0.05 radians. What does this tell you? Where and when can it be useful for your lab?

Experiment

First, you must level the Aluminum track in two directions. Start by checking the across-track leveling at both ends of the track using provided spirit level. After that is done, proceed to level the track in the along-track direction. Note that while doing this, **both** of the leveling screws at one end must be given the **same** number of turns to maintain the across-track leveling.

You can test the leveling of the track by taking some data using the cart and Motion Sensor II. Start data recording in Capstone, and launch the cart away from the sensor to the end of the track. Launch the cart with enough initial speed such that it can bounce off the end of the track. Record data for both away-from-the-sensor and to-the-sensor directions. Can you comment on the slopes of the velocity-vs-time plot? What do you expect for a leveled track?

Now design and perform an experiment to check your predictions. Describe carefully what you do, and explain any discrepancies between your predictions and the observations. Take at least 5 readings at different values of inclination of the air track. Then use your data to calculate a value of the acceleration due to gravity, *g*. Calculate your experimental uncertainty. This latter calculation must take into account precision and temporal resolution of the motion sensor. You can find it on the web site of PASCO and use later in the other experiments in this lab course
http://www.pasco.com/support/technical-support/technote/techIDlookup.cfm?TechNoteID=64

Notes & Hints

- You will be using Capstone in the experiment. For basic usage of Capstone, you should read the Appendix II. A Quick Guide to Capstone Software.
- Place the spacing blocks under the **both** leveling screws at one end to incline the air track**.**
- Launch the cart with MODERATE velocities (i.e. the carts should at most just make a slight click when they bounce off the stops).
- The Motion Detector has a short dead zone of **15 cm** within which the detector doesn't take any data.
- Set the beam setting (use the button on top of the Motion Sensor II) to short range (cart).
- In order to get good results, the Motion Sensor II **must be carefully aligned** to point exactly along the aluminum track. A typical syndrome of alignment issue is the appearance of unexpected spikes in the data.
- You can configure the Recording Conditions (e.g. measurement-based start and stop conditions) to help you taking the right amount of data in this experiment.
- Display your measurements of position and velocity on a graph in Capstone, and perform a curve fit to the desired portion of the data using the Highlight tool. Find the value of the slope from the

velocity graph and its error to extract *g*. Make sure you include all the errors (reading errors, instrument resolutions, etc.) in the error analysis.

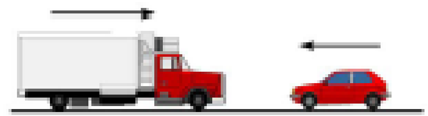
Questions. Answer the following questions in your report.

1. Can you observe the effect of friction in your velocity-time graph? If so, are the effects the same when the cart is moving up the track as when it is moving down?
2. Does your value of *g* agree with the accepted value for this latitude? Are there any other factors that can possibly affect your measurements?

Experiment 2. Newton's Third Law

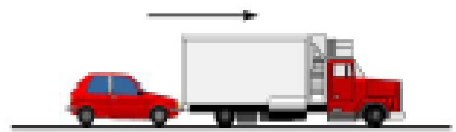
Preparatory Questions

1. A large truck collides head-on with a small compact car. Which of the following statements is true during the collision?



a) The force exerted by the truck on the car is greater than the force exerted by the car on the truck.
b) The force exerted by the truck on the car is the same as the force exerted by the car on the truck.
c) If the car is going fast enough, the force it exerts on the truck will be greater than the force the truck exerts on the car.
d) The forces exerted are a complicated function of the masses and speeds of the two vehicles.

2. Much to everyone's surprise, the truck is damaged more than the car, so the car driver agrees to push the truck to the garage. While the car, still pushing the truck, is **speeding up** to get up to cruising speed, which of the following statements is true during the "collision", if any?



a) The amount of force of the car pushing against the truck is equal to that of the truck pushing back against the car.
b) The amount of force of the car pushing against the truck is greater than that of the truck pushing against the car.
d) The car's engine is running, so it applies a force as it pushes against the truck, but the truck's engine is not running, so it can't push back against the car; the truck is pushed forward simply because it is in the way of the car.
e) Neither the car nor the truck exert any force on the other, the truck is pushed forward simply because it is in the way of the car.

Experiment

Use the force sensors and the collision carts provided to confirm (or disprove!) your answers to the Preparatory Questions. Make several runs with different loadings of the trucks. Make sure that you describe clearly your procedures in the notebook.

- If this is your first experiment you should read the Appendix II. A QUICK GUIDE TO CAPSTONE SOFTWARE.
- If you have already done the Experiment I, pay attention to the difference in PASCO sensors used for the first two experiments.
- Before taking readings, press the TARE button on the top of the Force Sensors in order to zero the reading. It is common that after this step the sensor's reading is not zero indicating pressure on its surface in the absence of external forces. Think about how to account for this systematic error when interpreting of your results.
- It is up to you to set an optimal sample rate: if it is too slow (20 Hz), you will not collect enough information; if too fast (10 kHz) processing problems may arise. You want to set the sampling rate as high as possible as long as this does not slow down the Capstone software, so that you can capture as many data points as possible during the collision.
- Find resolution of the force sensor on the PASCO web site http://www.pasco.com/prodCatalog/CI/CI-6537_force-sensor/#specificationsTab or

http://www.pasco.com/prodCatalog/CI/CI-6746_economy-force-sensor/#specificationsTab depending on the specific force sensor in your setup.

- When data is taken at high sample rates the computer may become irresponsive. Follow the instructions in Hardware Configuration section in Appendix II to speed things up.

Analysis

After recording the forces data, you can now analyze the difference between the forces involved in this experiment. Use the Calculator tool to create a formula for the difference D between the two forces(See Appendix II for the usage of the Calculator tool). For the variables you used in this formula, define them to be the force data you have taken (e.g. *Force, ChA/B)*. Using the Σ pull-down menu on the graph toolbar, you can obtain various statistics for selected data, such as the *Mean* and *Standard Deviation*.

The difference D between forces may not be exactly zero for all points. Why not? Does this mean a deviation from Newton's 3rd Law occurs at the non-zero points? To answer these questions, and to quote a quantitative limit on how well you have confirmed the Third Law, proceed as follows:

- Create a histogram by dragging the *Histogram* icon from the *Displays* palette on the right. Note that by selecting a portion of the D graph, the associated histogram will display information for that section only.

- Use the *Histogram* toolbar to adjust the histogram and give the best display (e.g. you can increase the number of bins and auto-scale the graph). Note the shape of this distribution. Does it appear to be approximately Gaussian (i.e. Normal)? If it were assumed that this distribution is a Gaussian distribution, what percentage of points would you expect to lie outside three standard deviations from the mean? Is this expectation confirmed for your data?

Finally, if it appears from your data that the Mean value of D is not zero, it is worth checking if this is simply a matter of inaccurate calibration or a more systematic effect. *Question:* what does 'zero' mean here? Give an experimental answer. Take some more measurements if necessary, and discuss your results.

Experiment 3. Dynamics of Rotational Motion

Preparatory Questions

1. A figure skater is performing the spinning maneuver during a competition. Which of the following statement is true about her moment of inertia? Provide a brief explanation.

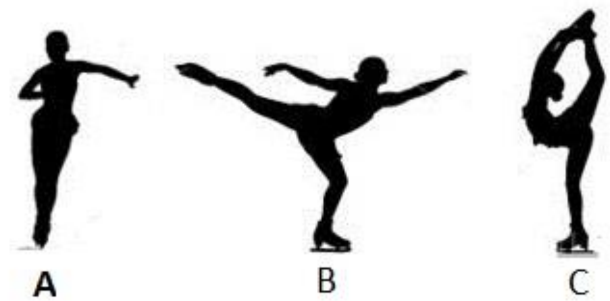


Fig. 1

a) Her moment of inertia is largest at Position A (Scratch spin)
b) Her moment of inertia is largest at Position B (Camel spin)
c) Her moment of inertia is largest at Position C (Biellmann spin)
d) None of the above. Her moment of inertia depends on her speed of spinning.

2. The skater launches the spinning maneuver and spins with each position with smooth transitions in between. Neglect the friction so that the angular momentum is conserved. At which position will the skater spin the fastest? Provide a brief explanation.
a) Position A
b) Position B
c) Position C
d) All of the above are possible.

3. In the diagram on the right, a rotational disk is attached to a string which connects to an object of mass ***m*** over a pulley. The downward direction is positive.
a) Find the relation between the linear acceleration ***a*** of the mass ***m*** and the angular acceleration ***α*** of the rotational disk.
b) Using the equation of torque for the drum, solve for the moment of inertia ***I*** of the system. Your result should only contain ***m, g, a*** and ***r.***

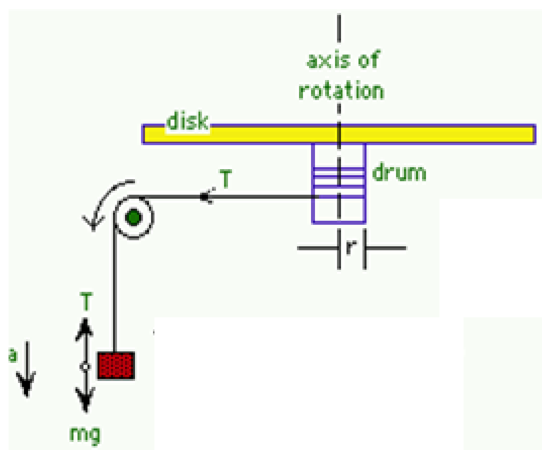


Fig. 2

This experiment is about the dynamics of rotational motion with the concepts of moment of inertia, parallel axes theorem and the law of conservation of angular momentum. The experiment consists of two parts and demands good time management to accomplish all exercises.

Part I. Moment of Inertia

Theoretical background

The property of a body by which it resists acceleration is called the inertial mass *m*. The rotational analogue to inertial mass is the moment of inertia *I*. It is the property of a body by which the body resists angular acceleration. Newton's second law of motion for linear motion $\vec{F} = m\vec{a}$ has a rotational analogue, which is

$$\vec{\tau} = I\vec{\alpha} \qquad (1)$$

where $\vec{\tau}$ is the torque and $\vec{\alpha}$ is the angular acceleration.

In this experiment you will determine the moment of inertia of a hollow cylinder about the axis of symmetry by applying torque and measuring the corresponding angular acceleration with PASCO *Rotary Motion Sensor*.

For rotation about the axis of cylindrical symmetry the moment of inertia of a hollow cylinder of finite thickness is

$$I_{hollowcylinder} = \frac{1}{2}M\left(R_1^2 + R_2^2\right) \qquad (2)$$

where R_1 and R_2 are the internal and external radii of the hollow cylinder.

Experiment

In this experiment, data is taken using rotational motion sensors (RMS). Find specifications for the Rotary Motion Sensor on the PASCO web site
http://www.pasco.com/support/technical-support/technote/techIDlookup.cfm?TechNoteID=1064

- The aluminum disk with a square hole in the center is mounted above a three-step pulley onto an axle penetrating the box with RMS (Fig. 1). The system is attached to a support rod of a massive stand for stability.
- Temporarily remove the aluminum disk, select the middle step of the three-step pulley and measure the radius of the drum.
- Attach a thread to the drum of the horizontal pulley by passing the thread through the hole in the pulley and tying a knot. Pass the thread over the vertical pulley and adjust the lateral position of the pulley for the particular drum radius that you have chosen.
- Mount the aluminum disk. Place a bubble level on the aluminum disk and level the stand. This means that the axis of rotation is vertical.
- Attach the vertical pulley to the rotary motion sensor with the plastic thumbscrew facing down as in Fig. 2. **Do not over tighten since the parts are made of plastic and are quite fragile.**

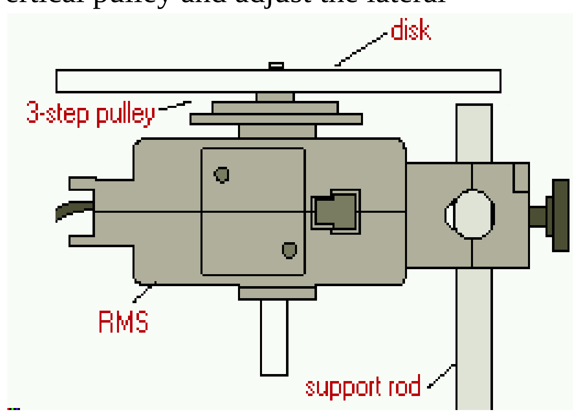


Fig. 1

- Masses are to be hung from a thread attached to the horizontal three-step pulley to provide a torque to accelerate the rotation.

- Adjust the height of the vertical pulley using the thumbscrew at the side so that the thread passing over the top of the pulley is horizontal as in the diagram. Make sure that the thread is long enough so that you can take enough data while the sensor is still accelerating, but not too long that the masses will hit the floor.

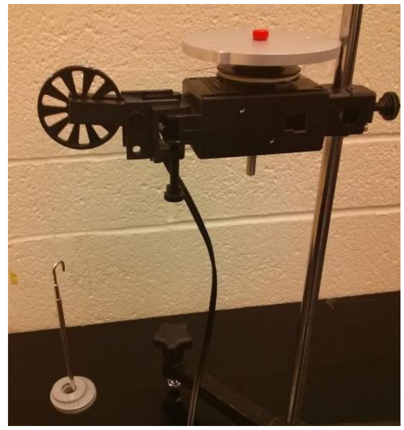


Fig. 2

Q1: How will making the string too long affect your experiment?

In Capstone, configure the hardware to use the *Rotary Motion Sensor*. Take some preliminary data to observe how the apparatus responds as the masses fall.

Moment of inertia of a rotating system without a hollow cylinder

Measure the angular acceleration for three different masses using the small masses with not more than three trials for each mass. Calculate the torque for each run and insert it to the data table as a new column. Plot torque versus angular acceleration and the slope of the graph will be the moment of inertia of the system.

Moment of inertia of a hollow cylinder (or a ring)

Mount the hollow cylinder on top of the disk with the protruding posts sticking into the disk to keep it in place. As above, measure the angular acceleration for three different masses (use the larger set of masses) with not more than three trials for each mass. Calculate the torque for each run and plot torque versus angular acceleration. The slope of the graph will be the moment of inertia of the new system which is the hollow cylinder plus the system for which the moment of inertia was previously determined. By subtracting, determine the moment of inertial of the hollow cylinder. Calculate the error.

Measure the mass and dimensions of the hollow cylinder and calculate its moment of inertia according to Eq. 2. Calculate the error.

Q2: Compare your results to those obtained with the first method, taking into account the errors of different measurements. Do they agree with each other? Why or why not?

It should be noted that when you are plotting torque versus angular acceleration you are not plotting two independent variables because the angular acceleration was used in the calculation of the torque. However, they are almost independent since in calculating the torque, αr is small compared to g.

Part II. Conservation of Angular Momentum

Theoretical background

One of the fundamental conservation laws of physics is the law of conservation of angular momentum, which states that the total angular momentum of a system is constant in both magnitude and direction if the resultant external torque acting on the system is zero. In this experiment, you will test the law of conservation of angular momentum and investigate some of the factors that determine an object's moment of inertia.

For rigid bodies that possess axial symmetry, the angular momentum $\vec{L}$ and the angular velocity $\vec{\omega}$ are parallel and we can write

$$\vec{L} = I\vec{\omega} \qquad (3)$$

where I is a scalar that represents the moment of inertia of the body about the axis of rotation. In general, the moment of inertia I is a tensor and $\vec{L}$ and $\vec{\omega}$ may have different directions, but this is beyond the scope of this experiment. For rotation about the axis of cylindrical symmetry, the moment of inertia I_d of a *solid* disk (cylinder) is

$$I_d = \tfrac{1}{2} MR^2 \qquad (4)$$

where M is the mass and R the radius of the disk. For rotation about an axis parallel to, but not through, the axis of cylindrical symmetry, the Parallel Axis Theorem states that the moment of inertia I is given by

$$I = I_{CM} + MD^2 \qquad (5)$$

where I_{CM} denotes the moment of inertia about the axis through the center of mass, and D is the distance between the axis through the centre of mass and the axis of rotation.

Experiment

There are two basic properties of an object that determines its moment of inertia, distribution of mass and geometry. Design your experiment to investigate such dependencies of the moment of inertia.

You can choose among the brass disk, the aluminum hollow cylinder and the brass hollow cylinder to perform measurements. Note that the aluminum hollow cylinder and the brass hollow cylinder have about the same physical dimensions but different masses, while the brass disc and the brass hollow cylinder have about the same mass but different shape. You will need to measure the mass and the radius of the chosen objects to calculate their moment of inertia.

Remove the vertical plastic pulley, the horizontal three-step pulley and the aluminum disk that you used for the first part of this experiment when measuring moment of inertia.

Mount the other aluminum disk with concentric circular lines on the rotary motion sensor. For removing or fixing the aluminum disk, use the hex key provided. Move the rotary motion sensor along the support rod closer to the base of the stand so that it is quite solid.

You will be dropping the chosen object onto the rotating disk. In order to keep the object centered on the disk you should arrange the apparatus to that you can look down on the apparatus from above.

Use the provided bubble level to level the aluminum disk by adjusting the knobs of the stand. Adjust until the bubble stays in the centre, which means that the axis of rotation is vertical. Place a small piece of double-sided tape on the disk to prevent sliding when you drop an object on to the disk. This is in analogy with perfectly inelastic collision in linear motion.

Give the disk an initial spin and start recording in Capstone. Using the concentric circles on the disc as a guide, drop the object of choice with its axis as close to the centre of the disk as possible, and observe the change in angular velocity. You many need to practice this several time before you become good at it. **DO NOT DROP OBJECTS ONTO THE ROTATING DISC FROM A LARGE DISTANCE. THIS WILL DAMAGE THE SENSOR AND GIVE ERRONEOUS RESULTS.** In fact, the closer you place the object to the disk before dropping, the easier it is for you to centre the object on the disk.

After the collision, let Capstone record a few more seconds of data. Stop the rotation and if you see deviation of the object from the centre of the disk, measure this deviation. Use the parallel axis theorem to determine the actual moment of inertia.

Q3: Calculate the angular momenta using angular velocities immediately before and after the collision. Does your experimental result confirm the conservation of angular momentum?

The rotational bearings of the apparatus are designed to have minimal frictional resistance. However, you may still observe the effect of friction from your data.
Q4: Calculate the frictional torque on the rotating disk before and after the collision. Is the frictional torque the same before and after the collision? Estimate an upper bound of the change in angular momentum due to the frictional torque (hint: the slope of the angular momenta before or after the collision gives the frictional torques; estimate the upper bound of the during of the collison).

Q5: Calculate the percentage loss of the rotational kinetic energy due to the collision.

Experiment 4. Simple Harmonic Motion

This exercise will give you an experimental introduction to the subject of Simple Harmonic Motion (SHM), which you will study in lectures later in the year. You may also find it useful to read relevant sections in your textbook.

Preparatory Questions

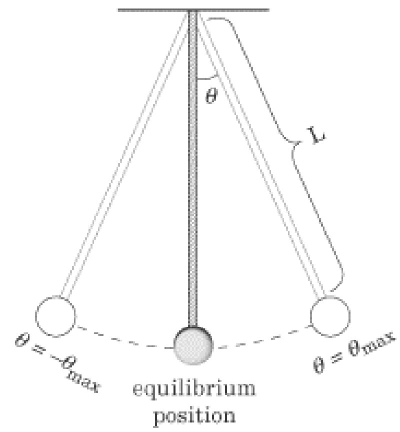
1. A pendulum with small swinging amplitudes (where small angle approximation is valid) is one of the simplest example of SHM. Which of the following statements is/are true?

a) The pendulum has its maximum speed when $\theta = \theta_{\max}$.

b) The pendulum has its maximum speed when it is at its equilibrium position.

c) The pendulum has its maximum acceleration when $\theta = \theta_{\max}$.

d) The pendulum has its maximum acceleration when it is at its equilibrium position.



2. Sketch the position, velocity and acceleration of an object in SHM.

Theory

Simple Harmonic Motion is the most fundamental of oscillatory motions. It occurs when an object is displaced from its position of equilibrium, there is a restoring force proportional to the displacement. The preparatory question provides one example of SHM. Another example is the small-amplitude oscillation of a mass on the end of a spring, where the oscillation is along the direction of the spring and the restoring force F on the mass obeys Hooke's Law

$$F = -kx \qquad (1)$$

where k is the spring constant, and x is the displacement from its equilibrium position. The acceleration due to the restoring force on the mass can be written as

$$a = F / m \qquad (2)$$

using Newton's Second Law . This can be written in the form of a differential equation:

$$\frac{d^2x}{dt^2} = -\omega^2 x \qquad (3)$$

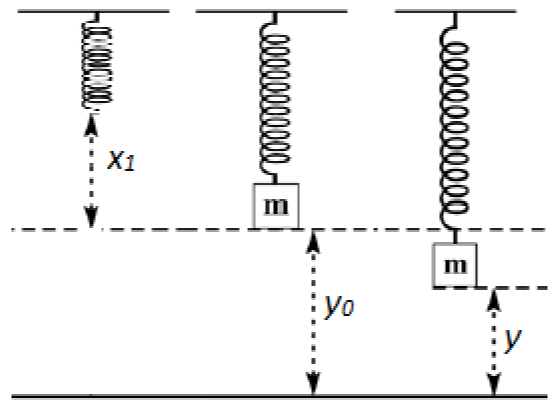
where $\omega = \sqrt{k / m}$ is the angular frequency in units of rad/second. The solution to this equation is

$$x = A\cos(\omega t + \phi_1) \quad \text{or} \quad x = A\sin(\omega t + \phi_2) \qquad (4)$$

where A, ϕ_1 and ϕ_2 are also constants.

The questions below are not for grading your answers but to help you clearer understand SHM.

1. Confirm by differentiation that $x = A\cos(\omega t + \phi_1)$ and $x = A\sin(\omega t + \phi_2)$ are indeed the solutions to the differential equation (3) of SHM.
2. ϕ is called the initial phase of the oscillation. What is the physical meaning of ϕ? How do the values of ϕ_1 and ϕ_2 differ for the same object in SHM?
3. What is the relationship between the frequency of oscillation f and ω? (Hint: f is the inverse of the period T and $\cos(\omega t + \phi_1) = \cos(\omega(t+T) + \phi_1)$).



To apply this theory to the experimental situation, consider a spring hanging from a support as shown. A mass m is attached to the end of the spring. As you will be measuring the displacement of the mass from the sensor, let us use the sensor as our new reference point. Let the distance from the sensor to the position of the mass be y_0 when the mass is at rest (in equilibrium). Then suppose that the spring is carefully extended so the mass is at a distance y from the sensor. Make sure that the extension you applied is less than the extension of the spring at the equilibrium position from the original position of the spring without a mass, *i.e.* $y_0 - y < x_1$. When the mass is released, SHM will ensue. In this case, starting time at a convenient instant, the equation governing the motion can be written as:

$$y = y_0 + A \sin(\omega t + \phi) \qquad (3)$$

Experiment

Suspend the spring from a stand, and position the Motion Detector under the oscillating mass. Remember that the Motion Detector will not detect motion at less than **15 cm**. Short pieces of string between the spring and the stand and the spring and the mass can prevent swinging and twisting of the oscillating mass.

Start Capstone and configure the motion sensor hardware. This experiment requires a higher sample rate than the default value. Choose a sample rate which allows you to sample at least 10 points during one oscillation.

Start the oscillation with a small amplitude (to ensure $y_0 - y < x_1$). Obtain data for 20 or so cycles of oscillation of the mass. Make sure the oscillations has similar amplitude. If you observe periodic amplitude fluctuations, there may be higher order modes of oscillation. If this happens, stop the oscillation and launch again with care being taken to ensure a small launch amplitude in the vertical direction.

Study the resulting Position, Velocity, Acceleration graphs. What are the relative phases of these variables? Why?

A quick and dirty way to find the oscillation frequency is to measure the time between a number of peaks (or troughs, or zero-crossing) of the sinusoidal wave, from which you can find the period of the oscillation and thus its frequency. A better way would be to use the *Highlight Data* and *Curve Fit* tool in Capstone to perform a curve fit for your data, and find the values of y_0, A, ω (or f) and ϕ.

Another useful way to determine the value of f is by *Fast Fourier Transform* (FFT). Consult the Appendix II if you have not done FFT in Capstone before. Note that the FFT gives better resolution in frequency as the number of points increases. We suggest that you take at least 1024 samples *(trigger rate* x *number of seconds observed)* to ensure a good resolution in frequency.

Now take measurements of Position versus time with at least 5 different masses, and find corresponding values of frequency, f. Input the masses and frequency values to a new data table and then add a graph in Capstone to plot it. Extract the value of the spring constant, k, from the graph.

Another way to find k is to measure the extension of the spring with different masses. Compare your results (with errors) and comment.

Optional Acquire more periods of data of the oscillator motion until you see significant reduction in oscillation amplitude. The motion deviates from the ideal simple harmonic motion due to inevitable friction and energy dissipation. You can fit the data to a damped sine function to find out the damping coefficient. There are many properties of the system that can be derived once you find this damping coefficient, for example, *the quality factor* and the change in oscillation frequency due to damping. Explore the topic of *damped oscillators* and comment on the experimental result you get.

EXPERIMENTS OF FREE CHOICE

The numbers in square brackets following the summaries, e.g., [1 wt], [2 wt], etc. indicate the number of weights credited to the experiment. A one-weight experiment requires one lab session (3 hours) to complete; a two-weight experiment requires two lab sessions (6 hours). Some of the two-weight experiments can be chosen for just a half of available exercises. In this case, they are considered the one-weight experiments.

The guide sheets for these experiments can be viewed and downloaded by clicking on the appropriate experiment in the list on the page "Experiments" of the course web site.

Mechanics and Mechanical Systems

- *Free Fall:* Measurement of *g* by determining the distance a body falls in measured time. [1 wt]
- *The Gyroscope:* A study of this fascinating instrument, in which angular momentum, torque, precession, nutation, etc., can be measured. (Not computerized) [1-2 wt]
- *The Mechanical Equivalent of Heat:* Joule's classic experiment. (Not computerized) [1 wt]
- *Conservation of Momentum and Energy:* The air track is used to investigate elastic and inelastic collisions and the drag forces with the motion sensor. [1 wt]
- *Oscillations of a Sphere on a Concave Surface:* Measurement of the radius of curvature of a concave surface using a simple harmonic motion system. (Not computerized) [1 wt]
- *The Torsion Pendulum:* Measurement of the torsional constant of a wire and the moment of inertia of various solids. [1 – 2 wt]
- *Wilberforce Pendulum:* A fascinating study of transformation of energy and mechanical resonance between two types of simple harmonic motion. [1-2 wt]
- *Chaotic Motion:* Study of forced oscillations, resonance and the cutting edge research of chaotic motion. [1 wt]
- *Materials Stress Strain Experiment:* Study of elastic properties of materials by stretching them until failure under the tensile load. [1 wt]
- *Static and Kinetic Friction:* Delicate experiment with a lot of options to study sliding friction [1 – 2 wt]
- *Viscosity by Capillary Flow*: Study of fluid dynamics with viscose liquids. (Not computerized) [1 wt]

Mechanical Models of Atomic and Nuclear Physics Phenomena

- *Scattering:* A model of a two-dimensional scattering process. The experiment simulates the scattering of a beam of particles from a fixed target (e.g. the Rutherford experiment with alpha-particles scattered by the gold nuclei that approved the Bohr-Rutherford model of an atom). (Not computerized) [1-2 wt]

APPENDIX I. SIMPLIFIED UNCERTAINTY ANALYSIS

This is a simplified look at uncertainty analysis. It is sufficient for what we expect you to do in the labs for PHY180. It is a first step in understanding uncertainty of measurements. There are some examples at the end of the document to help illustrate the calculations.

Systematic Uncertainties and Statistical Uncertainties

With few exceptions, when you measure something you cannot be completely certain that the value you measured is absolutely correct. An exception is when you count a small number, say 20 oscillations of a pendulum; then you can be sure it was not truly 21 oscillations.

There are two main types of uncertainties: systematic (or calibration or bias) uncertainties and statistical uncertainties. If repeated measurements improve your accuracy, you are dealing with a statistical uncertainty. If your ruler is inaccurate, that is a systematic uncertainty; using the same ruler multiple times will give you similar results which are all wrong by the same (unknown) amount. Quantifying and reducing systematic uncertainties is difficult and requires creative thinking. This document deals almost exclusively with the statistical uncertainties.

A common source of statistical uncertainty is the measurement uncertainty $\boldsymbol{u_m}$, which is the precision limitation of the device used to make the measurements (often called the reading error, although that is not a great name for it) which exist even if the device is perfectly calibrated. The measurement uncertainty $\boldsymbol{u_m}$ is usually the last digit of the measurement for digital devices, while for analog devices it is as good as your eyes are (often assumed to be half of the smallest value the device reads, but sometimes it can be smaller).

For repeated measurements, the statistical uncertainty $\boldsymbol{u_s}$ can be estimated from the data using statistics. Consider an experiment that is repeated $\boldsymbol{N}$ times, assuming the data points are **uncorrelated** to each other. The **standard deviation** $\boldsymbol{s}$ of your data gives the spread of the measurements – for any given measurement, there is a good chance for it to be within this spread from the average. If an experiment is repeated enough times, you should get the measurement uncertainty from the standard deviation. The statistical uncertainty $\boldsymbol{u_s}$, which quantifies the difference between the experimental result from the true value, can be estimated by $\boldsymbol{u_s = s/\sqrt{N}}$. So in the end you can report your result as $\boldsymbol{m_a \pm u_s}$, where $\boldsymbol{m_a}$ is the average of the measurements. Note that rigorously there is a correction factor $\sqrt{N/(N-1)}$ you need to apply in the calculation, but it is acceptable for the PHY180 Lab not to do so. As you probably noticed, the more repetition you do the smaller the statistical uncertainty. At some point, the statistical error will become smaller than systematic error and you can't improve your results by taking more measurements. This is when you need to analyze the experiment apparatus and method to see if you can reduce the systematic error in order to get better results.

Let's return to the pendulum example. You measure one period of oscillation with a stopwatch. The measurement uncertainty might be 0.01 seconds if you use a standard digital stopwatch which includes hundredths of a second. However, in this instance you should include the human reaction time as part of the measurement device. It seems plausible that the human's reaction time might be 0.2 seconds such that the uncertainty from the stopwatch is negligible. You might conclude that the measurement uncertainty is 0.2 seconds. If you wished to be very thorough, you would devise an experiment to measure the human reaction time and use that value as your measurement uncertainty.

You can repeat the measurements to improve the uncertainty. One way to reduce the uncertainty is to measure the oscillation 10 times, with the measurements independent of each other. The uncertainty goes down as $\mathbf{1/\sqrt{N}}$. A better way is to time 10 oscillations of the pendulum. The 0.2 second uncertainty would then be shared equally by all 10 oscillations, resulting in an uncertainty of 0.02 seconds for the average period. Note that in this case the oscillations are **correlated** – if you count one oscillation to be slightly longer than it actually is, the consecutive oscillation may appear to be slightly shorter. In general, if you measure $\boldsymbol{N}$ oscillations, your measurement uncertainty for 1 oscillation will effectively decrease by a factor of $\mathbf{1/N}$. In this case, it is always better to measure $\boldsymbol{N}$ oscillations 1 time than measure 1 oscillations $\boldsymbol{N}$ times.

Another issue is propagation of uncertainties. If you wish to measure the average speed of a marble rolling along a flat, level table, the easiest method might be to measure how long it takes to travel a specific distance. You wish to measure the speed, but in fact you are measuring the distance travelled and the time taken to travel that distance, both of which have uncertainties associated with them. What should you use for the uncertainty in speed? The text book (Appendix B.8) gives a conservative (over) estimate of the errors. For the PHY180 Lab, you can **add in quadratures** to calculate the uncertainty for **independent variables**. For multiplication/division, use the percentage error; for addition/subtraction, use the error directly. That is

$$\begin{cases} \text{if } y = x_1 \pm x_2, \text{then } \Delta y = \sqrt{(\Delta x_1)^2 + (\Delta x_2)^2}, \\ \text{if } y = x_1 \cdot x_2 \;\; or \;\; \dfrac{x_1}{x_2}, \text{then } \dfrac{\Delta y}{y} = \sqrt{\left(\dfrac{\Delta x_1}{x_1}\right)^2 + \left(\dfrac{\Delta x_2}{x_2}\right)^2}, \end{cases}$$

where x_1 and x_2 are independent variables. You should keep **1 significant digit** in the final value of Δy, and keep y to **the same decimal place** when reporting the result $y \pm \Delta y$.

The final topic is how do you claim two independent results agree. For example, if you wish to prove the conservation of momentum you need to show that the momentum before equals the momentum after. One way to do this is to subtract the two values and show that the result is consistent with zero. A value is consistent with zero if its uncertainty is as large as its value. For example, using the above rules, the difference between 53 ± 3 cm and 51 ± 1 cm is 2 ± 3 cm. This value is not zero, but it is consistent with zero. In fact, the claim that 2 ± 3 cm is statistically different from zero is false.

What if the value had been 4 ± 3 cm? Statistics indicates that there is a 1 in 3 chance that any individual measurement will differ from the average value by more than the uncertainty, a 1 in 20 chance that any individual measurement will differ from the average value by more than twice the uncertainty, and a 1 in 100 chance that any individual measurement will differ from the average value by more than three times the uncertainty. Therefore 10 \pm 3 cm is likely to be non-zero and should be described as such, whereas 4 \pm 3 cm is still too close to zero to be declared non-zero. All these odds (1 in 3, 1 in 20, 1 in 100) are approximate values. (For the curious mind, in the discussion here we assumed the measurements to have a Gaussian distribution).

Examples

Ex. 1: A spring-launched projectile travels 2.5 ± 0.1 cm in the launcher and a further 15.4 ± 0.2 m (on average) through the air. The total distance travelled is the sum of the two distances, 15.425 m, and the uncertainty is $\sqrt{0.2^2 + 0.001^2} \approx 0.2$ m. So the distance is 15.4 ± 0.2 m.

Ex. 2: A ball rolls $d = 1.00 \pm 0.01$ m in an average of $t = 3.5 \pm 0.2$ seconds. Since we are dividing the distance by the time, we should use percentage error here. The distance uncertainty $\Delta d/d$ is 1% whereas the time uncertainty $\Delta t/t$ is 6%. So $\Delta v/v = \sqrt{(1\%)^2 + (6\%)^2} \approx 6\%$. Since $v = d/t = 0.2857\ m/s$, we have $\Delta v = 0.0174$ m/s. Finally, we report the average speed to be 0.29 ± 0.02 m/s.

Ex. 3: The period of a pendulum is **independently** measured 10 times and the values in seconds are: 5.3, 5.3, 5.4, 5.4, 5.4, 5.4, 5.5, 5.5, 5.5, 5.6. Each individual measurement uncertainty is 0.1 seconds. Average value is 5.43 seconds; standard deviation is 0.095 seconds (which is very close to the measurement uncertainty). The statistical uncertainty is $u_s = s/\sqrt{N} \approx 0.03$ s. The final value to report is then 5.43 ± 0.03 seconds. If, on the other hand, we time 10 oscillations once (they are no longer independent of each other) to be 54.3 seconds with a measurement uncertainty of 0.1 seconds, we should report the oscillation period to be 5.43 ± 0.01 seconds.

Notes on improving measurements: to improve your measurement, find your biggest uncertainty and fix it. For the spring launcher, you need more trials in order to decrease the statistical uncertainty of the distance travelled. However, the pendulum uncertainty is clearly a problem with the time measurement. In that instance, measuring 10 periods instead of one period should cut the time uncertainty (likely to be a human reaction time issue) by a factor of 10. In general, if your repeated measurements are all very close to each other, you need a better measuring device or procedure. On the other hand, if your repeated measurements have a lot of variability, you need to take more data to get a better statistical average and standard deviation (or you need to better control some of your random variables in the experiment – for example, perhaps the spring launcher is outside on a windy day, in which case moving it indoors would be a good idea).

References

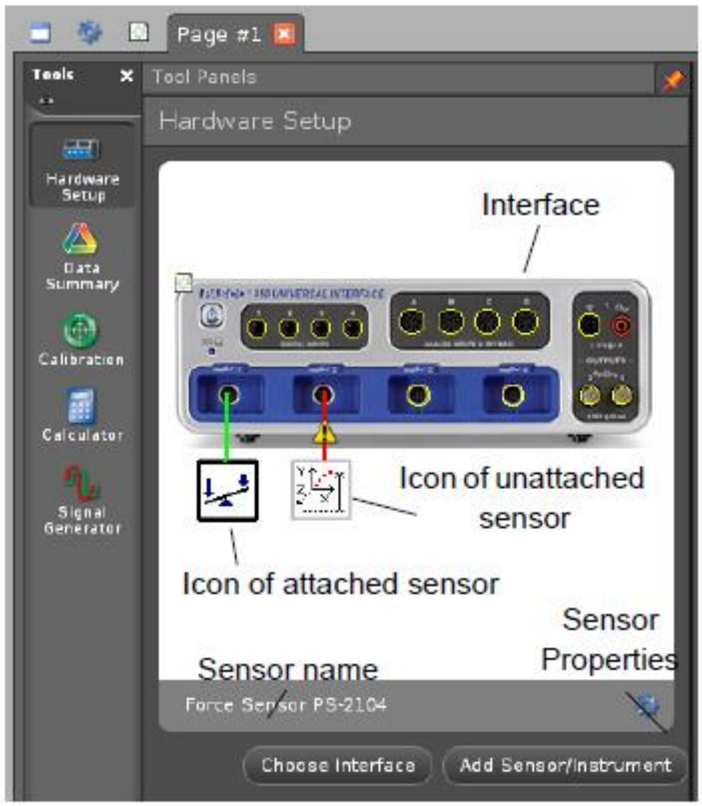
1. For a more in-depth look at uncertainty in physical measurements, take look at this page http://www.upscale.utoronto.ca/PVB/Harrison/GUM/ and all the links and modules therein.
2. A detailed treatment of error analysis can be found here: http://www.upscale.utoronto.ca/PVB/Harrison/ErrorAnalysis/.
3. The NIST Reference on Constants, Units and Uncertainty: http://physics.nist.gov/cuu/Uncertainty/index.html

Written by Brian Wilson, August 2014
Revised by Xingxing Xing, August 2015

APPENDIX II. A QUICK GUIDE TO CAPSTONE SOFTWARE

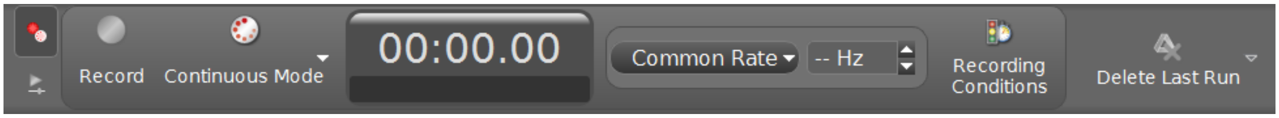
Hardware configuration

- After you start the Pasco Capstone software, you can find the Hardware Setup tool in the Tools palette.
- In general, the interface will automatically recognizes all PASSPORT sensors that you plugged into its inputs. For other sensors, click the input port into which you plugged the sensor. A drop down menu of sensors will appear. Select your sensor from the list of choices and the sensor's icon will be added to the picture of the interface.



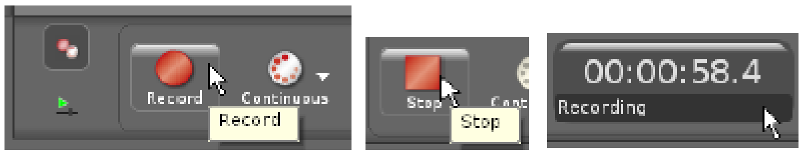
Hardware Setup panel

- If you opened a saved Capstone file with different sensor connections, you may observe an exclamation mark triangle ( ) indicates that the sensor is not connected or detected.
- You may configure the sensor by clicking the Sensor Properties icon in the lower right of the Hardware Setup tool.
- You may configure the sample rate of the sensor in Capstone. Note that the software may become irresponsive at high sample rates. Try remove graphs and displays to rectify this (or reduce the sample rate). You may also limit the number of samples by one of the following methods:
    1. Limit the total number of data points by reducing the data capturing time using the manual *Start* and *Stop*.
    2. Limit the total number of data points by setting Recording Conditions. There two type of conditions you can set: time-based or measurement-based. For example, for a force sensor, you can start recording when the force is larger or smaller than a predetermined value, and stop recording in 2 seconds after the start condition is met.



Taking measurements

- Click the Record button at the left end of the Controls palette to begin collecting data. The Record button changes shape to become the Stop button. Click the Stop button to end data collection.

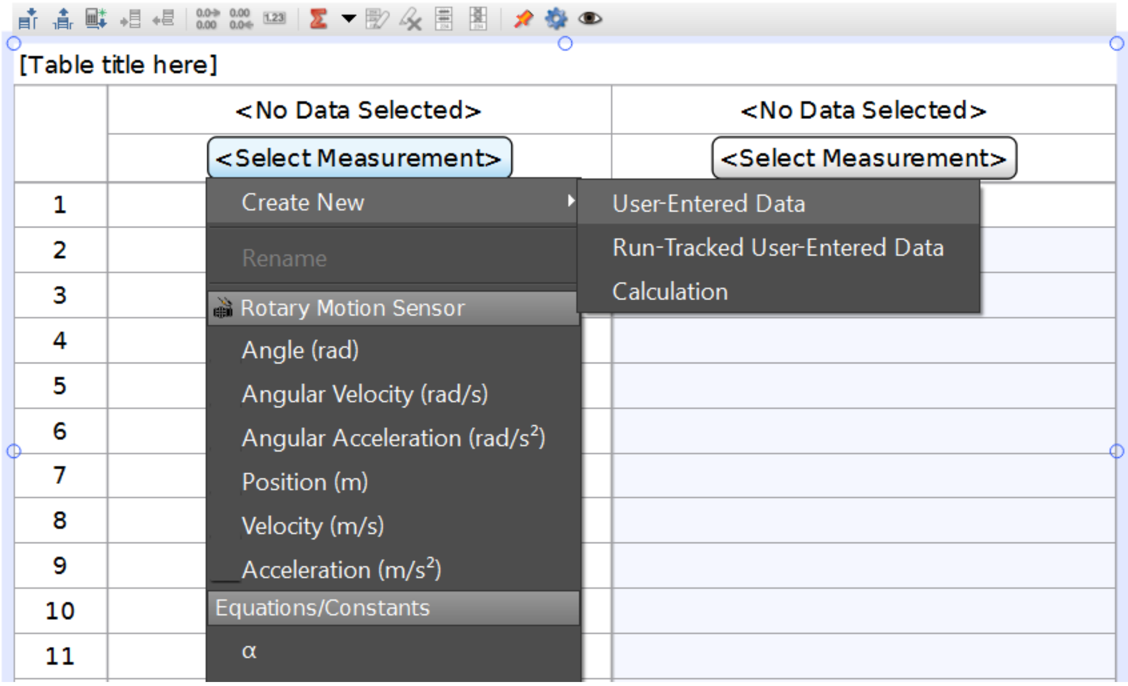


Record button, Stop button, and Experiment clock

- Repeat the process to collect multiple runs of data.
- To see a previous run of data in the display, click the Data Management button in the display's Tool bar and select the run (e.g., Run #2) from the menu. To delete a specific run of data, click the drop-down menu part of the Delete Last Run button in the Controls palette and select the run of data from the list page.

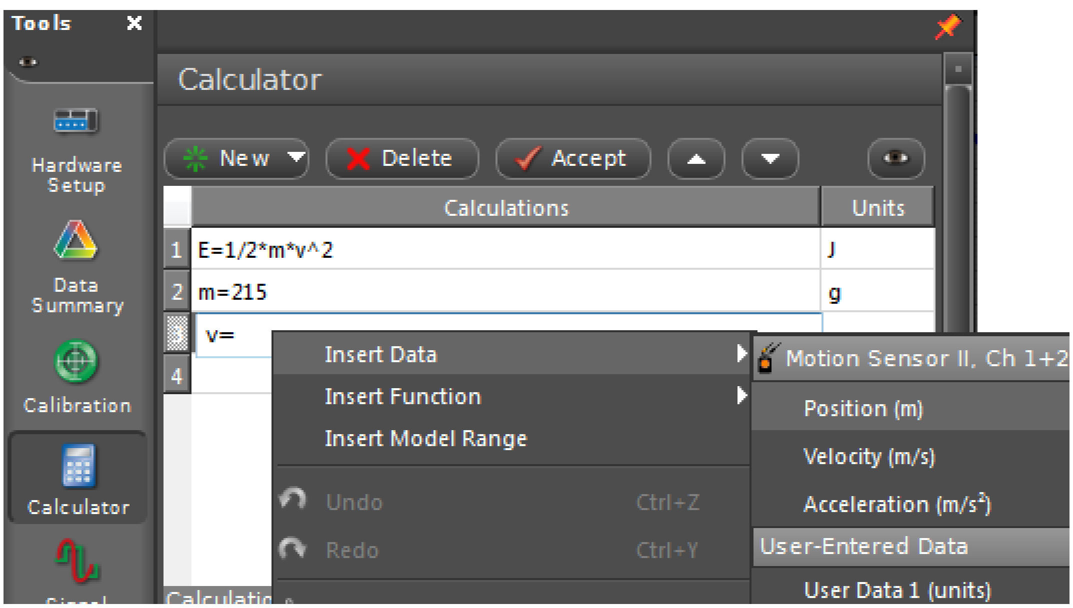
Data and Graph

- After data collection, you can view the data in a table or graph in Capstone. Choosing the desired variables to display in the table or graph at the dropdown menu. You can also input the data manually by selecting the *Create New* option.



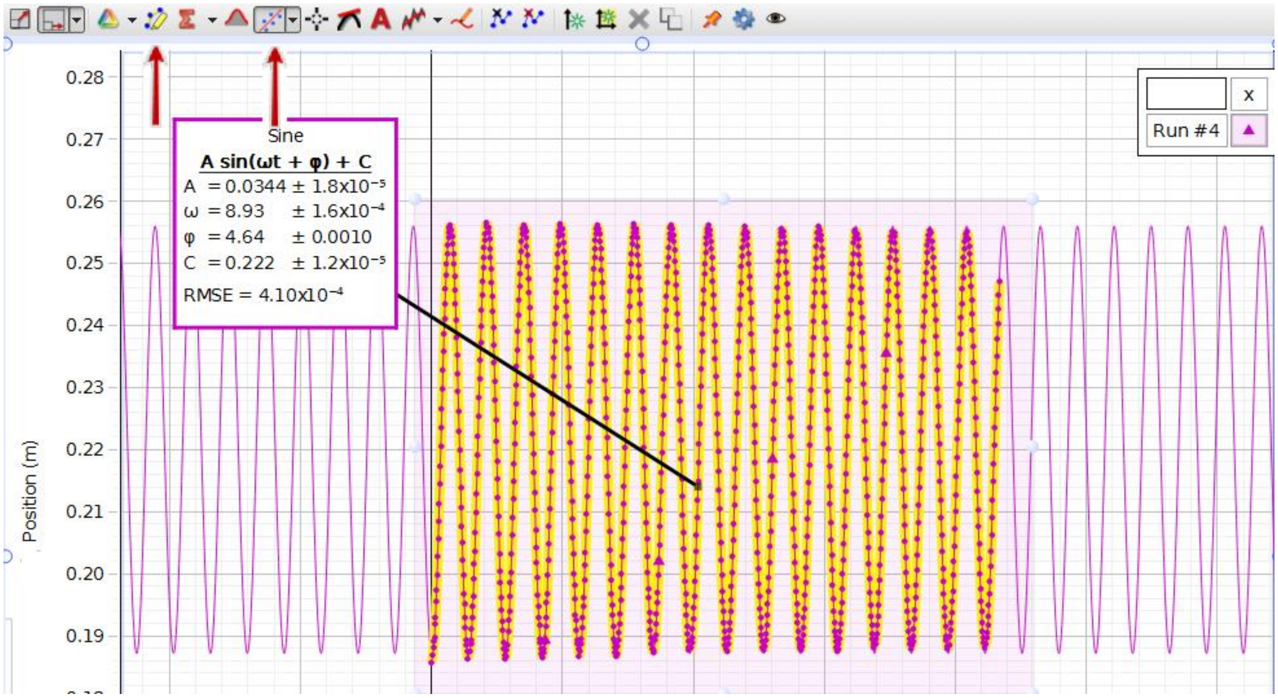
Select or create data in *Table*

- You can use the Calculator tool to perform complex calculations using a combination of math functions, measurements, user-defined data, constants, and text labels including symbols.



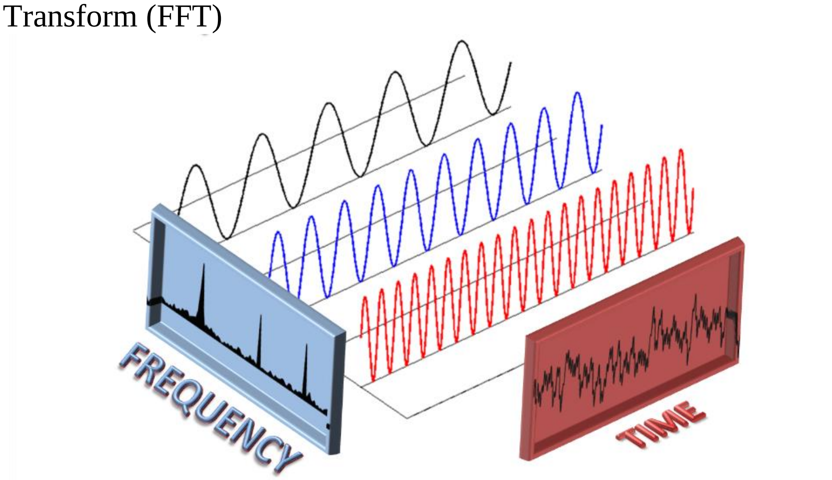
Calculator Tool

- The Curve fit tool provides a convenient way to fit your data to a model. First select the region of data you want to perform a curve fit using the Highlight tool , then choose a model using the dropdown menu and apply to active data.



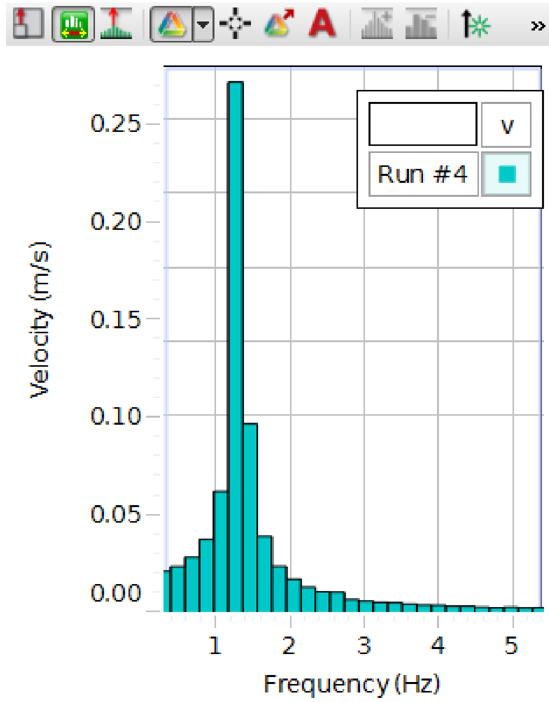
The data selection tool and curve fit tool

- Fast Fourier Transform (FFT)



A signal can be represented in both frequency and time domain. One can use FFT to conveniently transform the signal from one domain to the other. Image Courtesy: http://groups.csail.mit.edu/netmit/sFFT/algorithm.html

- To perform a FFT to the data in Capstone, drag from the *Displays* palette the *FFT tool*  and select the desired parameter on the y-axis. Note that you may need select the data set using the  button to activate the computation for FFT.



Fast Fourier Transform

Data files

- Recorded data is contained within the PASCO Capstone file (identified by the .cap extension).
- You may export the data to a .txt or .csv file for processing in your favourite third-party software (e.g. Excel, Python, Matlab, Origin, etc.).

Preliminary Exercise

Before starting compulsory experiments, you must get a short training in using the Capstone software to process experimental data. This exercise will allow you to familiarize yourself with the equipment and analysis tools. You are allowed to MP 126 to exercise in the use of the software on Monday proceeding the first lab session of the term.

- Training exercise: http://www.physics.utoronto.ca/students/undergraduate-courses/course-homepages/phy180h1lab/capstone

Resources and references

More resources are available on the Pasco website for Capstone and 850 Universal Interface

- http://www.pasco.com/file_downloads/product_manuals/PASCO-Capstone-User-Guide-UI-5401.pdf
- http://www.pasco.com/prodCatalog/UI/UI-5000_850-universal-interface/index.cfm

Note on the installation of Capstone

Capstone software is available in all the lab computers and in the computers in room MP257.

You can also download Capstone software from the Pasco website and install it in your personal computer. The link is: http://www.pasco.com/family/pasco-capstone/index.cfm. As of Capstone version 1.4.0.4, when installing, make sure to install to the default folder, otherwise the program may crash when you open an existing experiment file.