

## PHY151H1F – Laboratory Introduction

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Welcome to the first year physics laboratory! We hope that you will have an enjoyable and rich learning experience in labs. The experiments will enable you to grapple with many of the complicated and infuriating aspects of the real world, and begin to discern the connection between 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 understand the design of intelligent experiments
- solve practical problems
- keep complete records
- manipulate equipment in measuring instruments
- 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
- work effectively in a team of 2 or 3 people
- utilize resources and seek help when necessary

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. While your understanding of many physics ideas will be greatly enhanced by seeing their manifestation in the real world, the lab section is mainly interested in giving you the opportunity to learn the *experimental* techniques which make this connection possible.
- **train you to follow instructions.** Some undergraduate labs provide step-by-step directions for performing standard experiments. While this may be appropriate in some sciences, Physics has no finite set of rules by which experiments are designed and done. Within a fairly well defined context you will be expected to create your own direction and find your own path of exploration.

### GETTING STARTED

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

- A calculator. Many calculations are most easily done in excel on a computer, or you may prefer to use an app on your phone. However, keep in mind that computers and phones are NOT allowed a phone during a test or exam. Therefore, you should be getting used to using the same calculator you will have during your test and exam, and we recommend you use this during labs.
- A good clear plastic ruler of at least 30 centimetres in length. You do not need a lab coat! You also do not need to purchase a notebook, as one will be given to you on the first day.

- It might be helpful to bring your USB memory drive for saving experiment data.

### STRUCTURE OF THE LABORATORY

Each section of the course has a three-hour lab session every second week. Each section is divided into **lab groups** with about 10-12 students. Each group has a Lab Demonstrator who provides supervision, guidance, organization, grading the write-ups, grading the in-lab activities, and gives assistance throughout the year. Although each Demonstrator has a specific group responsibility, all of them are available, along with the Lab Coordinators (Jason Harlow and Brian Wilson), to answer questions from any student in the lab. You will meet your Demonstrator on your first lab day.

Generally you will work in a **team** of 2 or 3 students. The teams will be scrambled about half-way through the semester, just before you begin experiment #3.

**Important!!** Learn the name, office number and telephone extension of your Demonstrator, and remember what he or she looks like. **Print your Demonstrator's name and your lab section and group number** on the front of your lab notebook.

Your **LABORATORY NOTEBOOK** will serve as an ongoing record of your work in the lab. Lab notebooks should be used for **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. Your lab note book stays in the lab.

### REQUIREMENTS

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

You are required to finish five experiments in each semester. Each experiment is designed so that it can be completed within one lab session. 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. The TAs will guide you in the beginning of the lab to understand the experiment.

### MARKING SCHEME:

|  |     |
|--|-----|
| Experiment Marks (based on work recorded in notebooks) | 75% |
| Error Analysis Assignment (due Oct.1)                  | 10% |
| Measurement Project (due Nov.5)                        | 15% |

During the marking of your notebook, your Demonstrator will be looking at your performance in the following categories:

- adequate and careful pre-experiment preparation
- good statement of experimental procedures

- a complete, chronological description of your activities in the notebook
- clarity of description in short and concise manner
- appropriately wide range of data displayed as it was taken, in well-labelled tables
- graphs and diagrams used appropriately
- graphs with both axes correctly labelled
- units used throughout
- data self-consistent with all errors indicated
- correct and intelligent use of error analysis
- calculations clearly indicated
- an overall impression of careful and accurate work, well understood
- "reasonable" measurements, errors, results and conclusions
- indications of limitations of the experimental method, with comments on possible extensions

### **Error Analysis Assignment**

The analysis of experimental error is one of the most important things that you will learn in the first year laboratory. To complete the error analysis assignment, you must read a series of web-pages on the topic, work through the exercises on these web pages, and fill out answers to certain questions on an answer template which you may print. The web-bages are at: <http://www.upscale.utoronto.ca/PVB/Harrison/ErrorAnalysis/index.html>

The answer template is at:

<http://www.upscale.utoronto.ca/PVB/Harrison/ErrorAnalysis/AnswerForm.pdf>

### **Measurement Project**

In addition to being able to take measurements and estimate errors, we also require you to be able to communicate in a formal written report. Each student should submit a 2-page measurement project this semester. The assignment is at:

<http://www.physics.utoronto.ca/~jharlow/teaching/phy151f13/measpro.pdf>

### **Hints On The Use Of The DataStudio Software**

To **create data**, in the *File* menu, select *New Activity*. In the *Experiment Setup* window, click on one of the inputs circled in yellow on the 750 interface and then chose the appropriate sensor. The sensor icon will appear in the *Experiment Setup* window. If, by mistake, you create an extra sensor, you can delete it by clicking on the sensor and pressing delete.

- One can **change the Sample Rate** for a Motion Sensor from its default value of 10 per second; however, increasing the sample rate produces a corresponding limit in the upper range (*Max. Distance*) of the Motion Detector. The lower limit (*Min. Distance*) is always fixed at 15 cm. One can also determine how to display the information gathered by the Motion Sensor - the defaults are *Position*, *Velocity* and *Acceleration*.
- To **change start and stop options** for a Motion Sensor, click on *Sampling Options* in the *Experiment Setup* window. In the *Sampling Options* window one can choose *Delayed Start* so that there is a short delay between pressing the *Start* button and taking data. The *Automatic Stop* feature is also convenient.
- To **prepare a graph to display your data**, double click on the *Graph* icon in the *Displays* window at the left of the screen or drag it into the active area of the screen

and press *Start*. The data will appear on the graph as it is taken. Similarly, to see the data in tabular form, double click or drag the *Table* icon into the active area. As each set of different data is taken, the numbered *Run* is listed in the *Data* list on the left. To display a particular set of data, just drag the *Run* icon onto the graph (or table).

- To **enter data by hand** and then graph and perform a fit to this data, use the following steps.
  1. From the *Experiment* pull-down menu, choose *New Empty Data Table*. 2. The pencil icon on the toolbar will be already depressed to allow “editable” data.
  3. Type your data in the x- and y-columns.
  4. Release the pencil icon (this indicates an end to data entry).
  5. Drag the *Editable Data* icon in the *Data* window onto the *Graph* in the *Display Window*.
  6. Perform the fits using the pull-down *Fit* menu in the Graph window toolbar.
  7. Note that by double clicking on the *Editable Data* icon in the *Data* window you can change the name of the data set and the names of the variables.

### Data and Format Manipulation

- To **change the *Data Properties*** (e.g. the measurement name, colour in a graph or number of decimal places in a table of data) double click on the appropriate *Run*.
- To **make the data fit the display area** click the *Scale To Fit* button located at the extreme left hand corner of the tool bar on the graph. Also, you can drag the cursor over a portion of the graph (which will then be highlighted in yellow) and the highlighted area will fill the display area when you click the *Scale To Fit* button. Click the graph background to deselect the highlighted area.
- To **obtain the exact coordinates of any point** on the graph, use the *Smart Tool*.
- To **align the X axes** for two data sets having different variables but which are displayed on the same graph (e.g. position and velocity), click on the padlock icon.
- To **delete a specific run** click on the run in the *Data* list on the left and use the delete key on the keyboard. During an experiment you may want to **perform several trial runs** and not save the data. Instead of using the *Start* button to start data collection, pull down the *Experiment* menu and click on *Monitor Data* to start collection. This will allow you to take preliminary runs that will be automatically deleted until you are ready for final data taking.  
Alternately the *Experiment* menu allows you to delete ALL or just the last data run.
- To **delete selected points** from your data. Select (highlight) the data to be deleted on the graph. Drag the appropriate data in the *Data* list on the left onto the *Table* icon in the *Display* list and a table will appear with the data to be deleted highlighted. Click on the pencil icon → *Ok* → *Yes*. This creates an editable copy of your data (the original data is maintained unaltered). Right Click → *Delete Rows*. Double click on the appropriate graph in the *Displays* list to see the changes.
- To **export data** for use by EXCEL, use the *Export Data* option in the pull-down *File* menu. (See also the Data Fitting Techniques section in APPENDIX 1 of the Laboratory Manual.)
- The use of DataStudio Acceleration data (which is calculated data) is not recommended for your analyses. Since it is calculated from successive differences, the

acceleration values have a large spread (drag the Acceleration data on to your graph if you don't believe us!). Rather, use the Velocity values calculated by DataStudio, and extract the acceleration as required by fitting the data to a straight line.

- If you need more help in using the DataStudio software, first try the *Help* feature; if that fails, ask your Demonstrator!

## **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, add a folder with the button "Folder +" which will contain all your experiment data. The memory of the Content Collection is 50.00 MB.

On the laboratory computer you may save your files using a USB flash drive or in a folder *My Documents*. It is possible to borrow the USB memory stick from the Resource Centre for the current lab session. Save your work in *My Documents* periodically to avoid accidental loss of data. However, this storage should only be considered as a temporary one, since the contents of the folder *My Documents* is deleted daily as a part of rebooting the lab computers.

## **PRINTING GRAPHS**

To print out the data, you can use a default printer *hp 4050* in the laboratory room MP 126. The Lab Demonstrator will expect from you only the graphs that are used or are referred to in the text of your write-up. Too many graphs may sometimes decrease your mark, as they show that have not perfectly understood the objective of the experiment. As the printer is usually overloaded with printing at the end of the session, you will have to wait in a line until your task is done.

As the printer is usually overloaded with printing at the end of the lab session, you will have to be patient and wait until your task is done. 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.

## **RESOURCE CENTRE**

The Resource Centre is storage of equipment not assembled with setups in the lab space. To borrow equipment, come up to the window of the Resource Centre in MP 126 with your student ID, tell the technical staff what experiment you are doing and ask to provide you with the spares you need. There, you can also find some important handbooks and the course text book.

There is always an expert in technical issues working in the Resource Centre and available for students and lab demonstrators in the case of any equipment problem, including the problems with computers, software, interfaces, malfunctioning sensors etc. If you find that your setup is not functioning appropriately and the lab demonstrators cannot eliminate the source of the failure during 10 minutes, call for help from the lab technologist in the Resource Centre urgently. Feel free to do so without wasting your

time, as the technical assistance in the labs is responsibility of the lab technologist at the Resource Centre.

## DATA FITTING TECHNIQUES

### I. GRAPHICAL ANALYSIS

"A picture is worth a thousand words" is particularly true in the analysis of laboratory data. In many experiments it is very useful to check on the experiment by making a rough graph of the data points as they are being taken. Carefully drawn and analyzed graphs are often the best way to extract the values of the unknowns and to confirm or deny the theoretical hypothesis being tested. Finally graphs are important in presenting results clearly and pleasingly in a report.

Straight line graphs have a special significance. They are the easiest to draw by hand. In addition, their interpretation is often simplest, since all straight lines plotted on an  $x$ - $y$  graph have the form

$$y = mx + b \quad (1)$$

where  $m$  is the slope of the line and  $b$  is the intercept on the  $y$ -axis. Usually  $x$  and  $y$  depend only on the known or measured quantities while  $m$  and  $b$  contain the unknowns which you are trying to find.

Though a plot of your data points in their raw form will not generally lie on a straight line, you will find that data can usually be *made* to fit a straight line. If there are two and only two unknowns in your experiment, it is often advantageous to put the theoretical relationship into the form of equation (1). For example, a lot of physical laws are expressed with an exponential function. Taking logarithm of both sides of the relationship, you can bring such function to the form (1). Often  $x$ ,  $y$ ,  $m$ ,  $b$  turn out to be quite complicated expressions (see the *Example* below).

In graphs which are intended to do more than simply indicate a trend in the data, you will need to indicate the uncertainty in each point. This is done by drawing "error bars" which are lines corresponding to the size of the error on either side of the data point - vertically for errors in  $y$  values and horizontally for errors in  $x$  values (see Figures 1 and 2 below).

### II. USING HAND DRAWN GRAPHS TO FIT A STRAIGHT LINE

When you are attempting to fit a straight line to some data points by hand drawing, choose a line which encompasses a majority of points and passes as close to all of them as possible, taking into account the errors (indicated by "error bars") which indicate the uncertainty in the position of the points. This "best" line is a graphical estimate of the "average" of the data. By seeing how far on either side of this "best" line you can draw other acceptable lines, you will be able to form a common sense estimate of the errors in the slope and intercept of this line (see Figures 1 and 2). Note that **all** points need not lie on the line and a scatter of points about



a theoretical curve is to be expected in the real world. However, deliberately ignoring a few points (without a good reason) because they spoil a "perfect" fit to the other points is very bad science.

### DATA FITTING TECHNIQUES

*Tips:*

- Use a sharp pencil or fine pen to draw your graphs.
- Plot the points in pen and the smooth curve in pencil so that you may easily redraw your fitted curve.
- Spread the data nicely across the available area by choosing the scales appropriately on the two axes. Your graph may or may not include the origin at (0,0).
- Avoid the use of an unnatural subdivision of intervals; use multiples of 2, 5, or 10 whenever possible (not 3!!).

### III. USING COMPUTER TO FIT GRAPHS

**CAUTION:** Although the computer provides a very powerful method of fitting and analyzing your data, it will not evaluate your experiment, tell you about the appropriateness of your means of fitting data nor generally provide judgement on how well the performance of your experiment is going. It is up to you to check carefully how the line visually fits the displayed data and to ensure that it makes sense. If your choice of errors is poor or non-existent, the computer's calculated error in the slope and intercept will be equally flawed. **The thinking part of the experiment is still your responsibility** [see the notes on the  $\chi^2$  below]!

For many cases when you need to fit data to a function (linear, quadratic, etc.) the fitter in DataStudio is fine. You may also use a fitter provided by MS Office program Excel.

#### a) Entering your data from DataStudio into Excel

##### 1) Data was taken using sensors and DataStudio

If your data in DataStudio was acquired using the sensors, double click on the *Table* icon in the *Displays* list or drag the icon onto a free area on the screen. If the data that you want does not appear in the table, click on the *Data* menu on the toolbar to select the run you want, or drag the appropriate icon from the *Data* list at the left of the screen onto the table. If you want to edit the data at this stage, you can do so in DataStudio by clicking on the pencil icon on the *Table* toolbar.

##### 2) Data Is To Be First Entered Manually Into DataStudio

If you wish to enter data manually into DataStudio, double click on the *Table* icon or drag the icon onto a free area on the screen. Click on the pencil icon on the toolbar. The title of the Table will change to Editable Data; the first row will be highlighted and you can type in your data. The *Table* toolbar has useful items to delete unwanted rows or insert new rows etc.

**Once your data is in DataStudio**, you need to save the data in a file for use by Excel. Use the *Export Data* option in the pull-down *File* menu. You will be asked to choose the

data you want to export. The data you highlight will be exported in text ( .txt ) form. Save the file on your local computer. Open a new Excel file and copy your data to the table either by columns or completely. Don't forget to assign as many columns and rows in the Excel table, as there is in your text file.

### b) Entering Your Data From Excel

As in 2) above, suppose you want to fit data that was not taken directly in DataStudio. In this option you can enter your data from Excel. This is done in the reverse order with respect to the described above. The best way is to create an intermediate .txt file, copy the data from Excel in this file, save it in *My Documents*, and then enter the data in the DataStudio table.

### The Chi-Squared ( $\chi^2$ ) test

A value called *Chi-Squared* (the Greek symbol is  $\chi$ , pronounced like "cry", without the "r") is a statistical quantity which tells you something about the quality of your fit. (You will come across the quantity  $\chi^2$  in procedures in which averages are derived from data or in which curves are fitted to data, curve fitting being just another form of averaging.) For the case of the curve fitting like a least-square fitting procedure described above, the value is calculated by taking the sum of the squares of the deviation of each of the  $n$  data points from the fitted curve and dividing by the square of the error (= standard deviation) in each point:

$$\chi^2 = \sum_{i=1}^n \left[ \frac{\text{observed value}_i - \text{expected value}_i}{\text{error in observed value}_i} \right]^2$$

The size of this quantity depends on how well the curve fits the data, taking into account the fact that if the errors are large, a greater degree of deviation is expected. Its value will obviously depend also on the number of terms in the sum, equal to the number of data points. For a good fit, we might expect that, on average, each point might deviate from the fitted curve by approximately the value of the stated error, *i.e.* the sum in the equation above would, on average, have a value approximately equal to the number of data points, or approximately the number of degrees of freedom, if the number of extracted parameters is small.

If we have overestimated the errors,  $\chi^2$  would be too low. If even some of the points deviate from the fitted curve by more than we expect from the size of the errors,  $\chi^2$  will be too high. In fact, if we define the *degrees of freedom*,  $\mathbf{v}$ , as  $\mathbf{v} = \mathbf{n} - \mathbf{m}$ , it can be shown that, on average, the "expected value" of  $\chi^2$  is equal to  $\mathbf{v}$ . If your value of  $\chi^2$  deviates greatly from  $\mathbf{v}$ , you should suspect the goodness of your fit to the data.