PHYS 339 – Measurements Laboratory

(Rev.1.1: 05-Jan-2024)

Lab Hours / Office Hours	Tuesdays & Thursdays 14:35-17:25
Instructor	Dominic Ryan
Technician	Robert Turner
TAs	Daniel Lessa Coelho, Roman Akhmetshyn, Jiajun Cai

Aim of course

In this laboratory course you will:

1. Learn how to use computers to automate data acquisition and control experimental setups
2. Learn how to use computers for data analysis and display
3. Be reminded how to evaluate the uncertainties on measured quantities
4. Learn to present results in a formally structured report.
5. Carry out a self-generated/self-guided project.

Structure of the course

The core hardware of this class will be the *Arduino Uno*, a micro-controller that enables a computer to send digital and analog output signals to control various experimental devices and accept digital/analog inputs. While you may use any programming language that your lab group can agree on, the standard, *supported* language of the class will be *Python* (version 3.9). You will learn the basics of writing Python scripts, programming the Arduino and interfacing to the Arduino via Python. The experiments have been chosen to accomplish a number of inter-linked objectives with increasing complexity: (1) learning basic Arduino skills, (2) learning basic Python programming in the Spyder environment, (3) introducing different input/output (I/O) capabilities of the computer/Arduino interface and (4) show-casing advantages/possibilities of experimental automation/control.

The first lab introduces the Arduino functions and uses serial communication to take data "by hand". In the second lab you will use Python to automate the communication and data collection. Labs three to five explore progressively more complex tasks that the Python/Arduino system can perform. Finally, you will have the opportunity to perform a longer project experiment. The last four of these units must be written up as an official report, for which guidelines are given separately.

The "official" periods for the course are Tuesday and Thursday afternoons; I and the TAs will be available for assistance throughout this period. Robert Turner has the misfortune of occupying an office within the lab, so there is a very good chance that you will be able to find him on other days. I am running PHYS-359 in the lab directly across from the 339 lab on Monday and Wednesday afternoons, so you may be able to catch me in there.

You will form groups of two. *Your grades will be based solely upon the lab reports that you are expected to turn in after every lab*. The report must be a cohesive piece of work, not multiple disconnected reports handed in together. Each member of the group will be receiving the same grade for their group's work. Choose a partner that you can work with as it is extremely difficult to makes changes once the class is underway. Learning how to collaborate in research and writing papers is a key aspect of scientific research (and also careers in industry). Note that it would be wise for individual groups to discuss how they plan to manage work-loads/divide responsibility. One possibility is for a group to declare a "leader" for each lab who will be responsible for interfacing with me and turning in the report (but this is entirely up to you).

While you will not be *required* to keep a formal log-book to be turned in and graded, you need to document all of your data and record your work, so that your report has sufficient documentation and detail. If you are in doubt about what to record during an experiment, record it. You cannot look up things you didn't write down! *You are required to keep all raw data files used in creating the report, but these do not need to be turned in*.

Marking scheme and Deadlines

The first two sections will simply be graded pass/fail as they represent foundational requirements for proceeding. Your standing will be evaluated by demonstrating functioning code for some of the exercises. You must convince the TA that you are ready before you will be permitted to continue (*i.e.* "pass" is the only real option). The three main experiments will be graded on the basis of your reports, as will the project. If you start "slow" but finish with a strong project, I will consider increasing the weight of the project report to 50%, but iff this leads to an increase in your final score of more than 6%.

Item	**Due Date**	**Weight**	**Minimum Requirements**
Arduino	Jan 16, 17:25	P/F	No report – pass/fail evaluation by TAs
Python	Jan 23, 17:25	P/F	No report – pass/fail evaluation by TAs
Geiger	Feb 9, 10pm	20%	10 Page maximum (not counting title page and references)
Laser	Feb 23, 10pm	20%	10 Page maximum (not counting title page and references)
Servo Loop	Mar 16, 10pm	20%	10 Page maximum (not counting title page and references)
Project selection	Ongoing		See details below
Project proposal	Feb 21, 10pm	5%	2 page maximum
Project Go/No-Go	Feb 28		
Last orders	Mar 14		Cannot promise delivery after this date
Project start	Mar 18		
Project report	Apr 9, 10pm	35%	15 Page maximum (not counting title page and references)

A rough outline of the reporting requirements and their approximate weights:

20%	Correctness of the measurements
25%	Quality of the measurements
10%	Correctness of the analysis
10%	Discussion and presentation of uncertainties
20%	Structure and readability of the report
10%	Use of supporting information
5%	Aesthetics of figures

NOTE: Failure to address feedback in subsequent reports will incur a 1-grade penalty

Special requirements for the projects

The project component of this course places new demands on both you, and us. You need to find and design a practical project, while we have to both protect you from poor choices and support the good choices by making the required equipment available.

We will advise and help, but *you* remain responsible for the choice, design, and conduct of your project.

Roughly a third of the projects that get past us turn out to be physically impossible (the effect does not exist, the signal is orders of magnitude too small to be detected…) but time constraints or poor proposal writing limited our ability to evaluate them. A further third turn out to be impossible with the selected equipment or experimental design. It is essential that you "run the numbers". Estimate the size of the effect you are looking for, understand the range of parameter space that you have access to. Think about what you *actually* measure. *Nobody* measures the speed of sound. It is always derived from something else: wavelength, phase shift, time delay…

Everyone underestimates the time needed to get things set up and working (or to discover that it is not working). In an attempt to reduce the impacts of these problems we have set a series of deadlines (in the table above) but you are encouraged (required?) to discuss your plans with all of us long before any deadline. If we issue a late "no-go" decision on your proposal, you will be faced with a very busy "break" designing a new project.

In order to help you with planning and time management we will introduce you to the Gantt chart. This is basically a bar chart showing the timelines and dependencies of sub-tasks in a project. For example, you cannot build a circuit until you have the components, they take time to arrive, but you cannot order them until you have designed the circuit. Knowing (or at least estimating) how long each step will take allows you to determine *when* time-critical events need to happen. Any real project will have multiple threads, some of which can run in parallel, others run in series. Gantt charts allow you to see how steps are related so that you can avoid delays.

Many of the projects will require us to find or order specific items. We will do our best to accommodate requests, but we cannot work miracles. Last orders will be accepted on March 14th, after that you may not be able to get unanticipated components (it may be too late even by March 14th). Remember, *you* are responsible for your project, we only help. Your failure to plan does not constitute a crisis for us.

Use of supporting materials

All experimental work relies on the work of others – give credit where it is due. With very few exceptions (π and *e*, for example) the values that you use in physics are *measured* (*e.g*. the charge on the electron, the speed of sound…) and therefore the work of experimentalists. Do not ever describe them as "theoretical values". They are not. Theorists are already insufferable, do not make them worse by giving them credit for the work of experimentalists.

Cite any book or research paper that you use. Make sure the citation is sufficiently complete that somebody else can find it. It is rare that you would use an entire book, so cite the chapter, section or page(s) that you used, not the whole book. Cite the actual journal or book, *not* some random weblink that you found it on.

The lab handout, instructor, technician and TAs are officially "unreliable" and *must not* be cited. Trust but verify – find a primary source of any information. Just to be clear: lab handouts from another university or department, someone who took the course last year, a rando you met in a bar… are all "unreliable".

Report Requirements

- **TEMPLATES: We provide latex/lyx templates that you must use, unmodified, for all reports**. These templates put all reports on equal footing (fairness), are optimized for structured writing (better and more consistent guidance) and easy reading (better feedback). Reports compiled with a different / modified template will be automatically docked a full letter grade.
- Use the file name format **"Proj1-(Interm/Final)-Experiment-LastName-LastName.pdf**" to help us organize. Use one word for Experiment, e.g. Servo, Geiger, *etc*. This naming convention is *not* optional!
- Make sure they are exported as a PDF submitted through *myCourses*.
- Page limits do not include the title page, abstract page, bibliography, or any appendices.
- **Late Reports will be docked one full letter grade (10%) per day** (starting precisely at deadline (22:00) each day).

All reports contain

- **A title / author page**
- **Abstract page**
  - A single, short, paragraph:
    - (Optional) One sentence motivating the work.
    - A few sentences concisely summarizing the subjects and methods in the report.
    - A few sentences summarizing the progress made, listing key results, and comparing with expectations when relevant.
    - (Optional) One or two sentences for other key thoughts, implications, etc.
- **Body**, including requirements listed in the table on page 1.

Advice on Organization and Writing of the Reports

General Advice

- We are here to help you design your reports and figures. Our goal is for you to produce the highest-quality report, so that it is above the bar in all categories outlined above.
- To save time (this is based on the workflow in real research labs):
  - Sketch the figures you wish to present before you even begin taking the data. This plan will allow you to stay focused. Then proceed with the suggested experimental process described in the 'Structure' section above, generating the 'real' figures.
  - Design and assemble your figures prior to writing the report such that they convey the story you wish to tell (I.e. create a story board). Then writing generally is a breeze: describe the story that is in front of you!

Importantly, reports should be organized *serially*, with each section containing a complete story about a particular type of measurement. They should **NOT** be organized "in parallel", with (1) a section introducing *everything,* (2) a section discussing *every* measurement technique, (3) a section showing *all* data, and (4) a section containing *all* the analysis including uncertainties. This follows the convention how most professional papers (or theses) are written. Break the report into **self-contained, bite-sized stories** (usually one per measurement type), each having their own motivation, details, results, discussion, and systematic analysis paragraphs. This makes it much easier for you to write a coherent, logical report and for us to provide constructive feedback. In research papers it allows readers to follow and understand your discovery, without having to remember *everything* and carry *everything* in their head from section to section, which is impossible, forcing constant page flipping and text searching.

Specifically:

- A brief motivation for the measurement (a sentence or two, sometimes involving an equation).
- Details about how the measurement is performed, focusing on *differences* from the core functionality or measurements described in previous sections.
- Quantitative results and figures <u>including all uncertainties</u> justified in the caption or text. Usually there is one "punch line" figure panel illustrating the most interesting measurement, and a few panels showing "typical" data at each step leading the reader to this result.
- Quantitative discussion of the statistical as well as systematic uncertainties.
- A conclusion sentence or two, highlighting the most important points to remember from this section.
- All panels of all figures must be discussed, in order, in the main text, and, conversely, all data mentioned in the main text should have at least a "typical" example shown in a figure (at least in an appendix if it is not central to the story).

A good figure

- Has panel identifiers (a, b, c, ...) for multiple panels.
- Has labels and annotations of relevant / interesting features discussed in the text.
- Includes only what is important to the discussion and key details.
- Has a caption that is a self-contained description of the figure, <u>with every visible element mentioned somewhere</u>**,** including:
  - A caption title, e.g., "Apparatus for measuring pants."
  - Panel descriptions, highlighting all features of the panel, e.g. "(a) Dependence of raw conductivity σ on temperature T for Ge (blue curve), Cu (green curve), and Si (red curve) samples. Thermometer was positioned at point B in Fig. 1(c), and heat was applied with torch C in Fig. 1(b). [optional] The clear peak near T=320 K is visible above background only for the Ge sample, suggesting that a transition was observed."
- Captions should themselves represent a complete story for an expert in the field. The main text provides sufficient information for someone new to the field.

Justifying and Reporting Uncertainties

When reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results cannot be compared, either among themselves or with reference values derived from a theoretical model, a specification or reference standard. Evaluating and reporting uncertainties is central to science as well as technological and societal applications of measurements and data and is thus [internationally standardized].

There are two types of uncertainties, both need to be addressed to establish the reliability of the data:

Statistical: Make sure that you always *quantify* and *justify* all statistical uncertainties. They may come from the nature of the measurement (counting), variations established through repeated measurement (replication), or from fits to a physical model. Remember, a value without an uncertainty is just a number. It is *not* a "result" or a "measurement", and it has no place in your report.

Systematic: Quantifying systematics is one of the most important skills for an experimentalist. Rather than saying something like "our result could be off because the amplifier gain drifted", which is not useful or quantitative, we assign a number to it. A simple method for most cases:

1. Measure your main result using valid statistical uncertainties, assuming everything else works perfectly. This provides your statistical uncertainty.
2. Point out any inconsistencies or problems with the abovementioned result, e.g., statistically significant deviation from expected values, structure in residuals, high chi squared values – **all of which are okay as long as your method is correct and you don't ignore them.**
3. Identify a potential source of systematic uncertainty, and "wiggle" it. For example:
    - Repeat part of the experiment a different way or on a different day to see what is reproducible, what varies, and how this moves the main result.
    - Alter your calibration parameters over their uncertainty range and repeat the analysis to see how far it moves the main result.
    - Vary the fit region or fit function to see how this affects the main result.

You now have a new uncertainty associated with that systematic.

Reporting a systematic uncertainty can be as simple as a 1-2 sentence paragraph, e.g. "As shown in Figure 3, folding the data may cause lines to shift and change shape. If we perform the entire analysis *without* folding, the value a=[new value], corresponding to difference [difference]." After discussing a few systematics, you can summarize with something like "with a systematic uncertainty of [+/- difference] limited by [cause]." Ask us for ideas throughout your experiment, **and plan to do your experiment multiple times**!

Note that uncertainties are often colloquially called 'errors' and historically were evaluated using 'error analysis'. In modern measurement science we aim to quantitatively know how close our measurement is to the 'truth'. Clearly, uncertainty is not an 'error', it is an inherent part of any measurement. Note that from a philosophical point of view the only assumption here is that a 'true' value exists.

Appendices

These should generally be avoided. All too often they are used to "get around" page limits. If the information is important enough that you want us to read it, then it should be in the body of the report. If *you* don't think the information is important enough to be in the body of the report, then why should I read about it?

Report Checklist

Overall:

- All statements are precise and justified by data, previous text, or a citation. Put a number on it or don't mention it.
- Every measured or fit number has an uncertainty that is properly justified.
- All parts of all figures and equations are introduced in the text and/or caption.
- All new symbols are immediately defined in the text. Symbols are consistent throughout the report.
- All panels of all figures are discussed in the main text, in order.

All plots include these discussion points:

- The quantities that are shown (*i.e.*, what *vs* what) and the conditions under which the data were taken.
- How the shown uncertainties in y and x are estimated (or, most commonly, how you rule out x's uncertainty as negligible).

Fits include:

- Measured data as points (with uncertainties) fit(s) shown as one or more lines.
- Fitted curve(s) and the equation(s) used are identified.
- Which parameters of the equation were fixed, and which were floating.
- Values of all fit parameters with units and uncertainties (typically in a table if there are a lot of values or many similar fits).
- The value of reduced chi^2, the degrees of freedom (or standard deviation), and how likely this value is.
- Studentized residuals and a discussion of any structure (or lack thereof).

Formatting, etc.:

- Abstract includes list of major results and (when possible) a comparison with expectations.
- You used the template: output looks like the template output.
- Body fits within the page limit.
- Figure fonts are no smaller than 2/3 the body text size.
- A final spell-check has been run.
- File name is of the form "**Proj1-Rep1-Experiment-LastName-LastName.pdf**".
- Submit to the correct assignment/group on myCourses.

Python resources

- Python tutorial: from data files to fits to figures. If you're interested
    - Install spinmob/mcphysics: https://github.com/Spinmob/mcphysics
    - Make sure spinmob is working
    - Familiarize yourself with python, e.g., https://github.com/Spinmob/spinmob/wiki/1.-Python-Boot-Camp

Fine Print

- In accord with McGill University's Charter of Students' Rights, students in this course have the right to submit in English or in French any written work that is to be graded.
- McGill University values academic integrity. Therefore, all students must understand the meaning and consequences of cheating, plagiarism and other academic offences under the Code of Student Conduct and Disciplinary Procedures (see www.mcgill.ca/integrity for more information).
- If you have a disability please contact the instructor to arrange a time to discuss your situation. It would be helpful if you contact the Office for Students with Disabilities at 514-398-6009 before you do this.
- In the event of extraordinary circumstances beyond the University's control, the content and/or evaluation scheme in this course is subject to change.
- Additional policies governing academic issues which affect students can be found in the McGill Charter of Students' Rights.