PHY180 Lab Project (2025)

This document outlines the lab experiments which you will do at home during the semester. Each student will be required to build a simple pendulum (for example, a mass swinging from a string) and then compare its performance with a specific mathematical model that theoretically should predict the behaviour of your pendulum. The goal of this project is to quantify and analyze how accurately the mathematical model represents the actual setup. **Note that your pendulum MUST have a variable length!** Keep this in mind when you design your pendulum.

This lab is scaffolded into sections, with separate due dates as shown in Table 1, so that you can get feedback at each step to be incorporated in subsequent steps. Each submission will include the previous work (with improvements as needed) so that the final report you submit is a full and complete record of the entire project.

Table 1: Due dates and weights of the three reports which will be submitted as part of the pendulum project. There is an additional 3% weight for the check-ins outlined in Table 2.

Section	Due Date	Weight 1	Weight 2
Lab 1: Period vs. Angle and Q Factor	1 Oct 2025	6%	3%
Lab 2: Period vs. Length and Q Factor vs. Length	7 Nov 2025	6%	3%
Final Report	28 Nov 2025	10%	16%

Note that the final report does not require any new experiments, but you are encouraged to take new data to address any concerns identified by your TA from reports 1 and 2. If your final report is better than your earlier reports, your grade will be determined by the Weight 2 column instead of the Weight 1 column.

In addition, there is a 3% credit for doing the check-ins as outlined in Table 2. Each check-in has 3 marks associated with it, and your total check-in grade is out of 12 (where the maximum grade is 15). In other words, each mark from the check-ins is worth 0.25% of your final grade, up to a maximum of 3%.

Table 2: Due dates for the check-ins. Your specific due date is the day and time of your practical. All check-ins must be done in person in the practical room during your assigned practical time.

Bring to Practical	Week of
Period vs. Angle graph	Sep 22 to 26
All Report 1 graphs with captions (discuss their features)	Sep 29 to Oct 3
All Report 1 graphs (discuss how to reduce uncertainties)	Oct 6 to Oct 10
All Report 2 graphs with captions (discuss their features)	Oct 14 to Oct 20
Introduction section of your report	Oct 21 to Nov 3

Rubrics for all three reports and all five check-ins will be posted on Quercus.

Taken together, this represents 25% of your mark in PHY180.

Expectations About Collaboration Versus Plagiarism

You are expected to discuss this project with your peers, your teaching assistants, and anyone else you wish to. You can even, with prior permission of the instructor, share equipment with another student.

You may not share data. You must take, and analyze, your own data. You can discuss how to analyze the data with anyone, but you must do the analysis on your own.

You may not copy text. When you are discussing the project with peers, you should never look at their written work, and you should never let anyone look at your written work. If you do so and then "accidentally" copy their words, that constitutes plagiarism, and all parties involved will get into trouble. That includes the situation of someone else copying your work; you are still party to the plagiarism and you can still get into trouble.

If you have troubles with writing the lab report and want assistance with how to write your paper, you are encouraged to contact (as early as possible) the **Engineering Communication Program**. Please visit their website at `https://ecp.engineering.utoronto.ca/` for more information.

Your paper should include references, citations, and possibly quotations (though in general we discourage quotations for a lab report). A reference is an item in your list of references. It tells the reader where to find a citation or quotation. A citation is an in-text notation that clearly indicates where something came from. It should be used, for example, to indicate where you got any equation which isn't "obvious" (Newton's laws are considered obvious). A quotation is similar to a citation except it must include quotation marks, and it indicates that the reference was used verbatim instead of paraphrased. Note that paraphrasing still means writing in your own words; if you copy text and modify a few words, that still counts as a quotation, and failing to use quotation marks properly constitutes plagiarism.

As an example, if you use equation (2) (see next section), you should cite where you found that equation. Presumably, you found it from this document, so you should cite it as (Wilson, 2024) in the text where you first mention it, and then you need a more complete reference at the end of your paper such as:

Wilson, Brian, "PHY180 Lab Project", downloaded from Quercus, 2024.

You can use any style guide for references and citations as long as it is clear. Where possible, citing published works is better than citing this document since this document is not published in the sense that it is not generally available for anyone to find.

Background: Mathematical Model

Here is the mathematical model that I think should do a decent job of predicting the behaviour of your pendulum. Note that I write this before you created your pendulum **so you should be skeptical**. The name of the model, should you wish to research it to learn more, is 'damped harmonic motion' or 'damped harmonic oscillator'.

Measure the angle (in radians where 2π radians is the same as $360°$) that the string makes from the vertical (with 0 being straight down) and call it θ. If you hold the pendulum at rest at some initial angle (θ_0) less than $\pi/2$ (90 degrees) and then let it go, I predict it will swing back and forth as described by the equation

$$\theta(t) = \theta_0 \, \mathrm{e}^{-t/\tau} \cos\left(2\pi \frac{t}{T} + \phi_0\right) \tag{1}$$

where t is time, ϕ_0 is called the phase constant (it would be zero if you start time at the exact instant you release the pendulum, but if there is any time delay then it will not be zero) and τ and T are quantities which are constants which depend on your set up. I have no good prediction for τ except that it is hopefully measured in tens or hundreds of seconds, but it basically measures the friction (technically, the viscosity) of your pendulum. Note that it is possible to make a pendulum which has a linear decay instead of an exponential decay by making kinetic friction larger than viscosity, for example by having your pendulum rubbing against a board. Try to avoid this.

I can predict that T (the period of your pendulum, that is how long it takes to complete one full oscillation) will have a value of

$$T \simeq 2\sqrt{L} \tag{2}$$

where L is the length of the pendulum in meters. Actually, it's the distance from the centre of mass to the pivot point. Note: the units for my equation do not work; you should fix this in your report.

Engineers use the Q Factor instead of τ. The Q Factor is defined as

$$Q = \pi\frac{\tau}{T}. \tag{3}$$

One of your tasks will be to determine how the Q Factor depends on string length L. I give you no prediction on this. (The lack of prediction is because it's complicated, and different pendulum setups get different results. If you're getting something different from your peers, don't panic.)

Background: Uncertainties

Very few quantities can be determined with absolute certainty. Counting small integers can usually be done with certainty. For example, I have exactly 10 toes. However, my height does not have a singular, certain value. It depends on the time of day, and any method used to measure my height will have both random and systematic discrepancies compared with using different methods to measure my height. **Basically, independent methods of measuring the same thing will almost always disagree at least a little.**

There are ways to correctly determine the final uncertainty of a quantity based on all the various sources of uncertainties that were involved in finding the final quantity but you don't need to follow those this year. You can simply identify the single largest source of uncertainty and claim it as your final uncertainty. Use the following 2 rules for determining which is the largest uncertainty.

1) If adding or subtracting multiple quantities, the largest uncertainty is simply the largest uncertainty. Example: $(3.5 \pm 0.2) + (13.589 \pm 0.006) = (17.1 \pm 0.2)$ since $0.2 > 0.006$. Note that you should round your uncertainty to one place and round the value to the same accuracy as the uncertainty, so it is bad form to write 17.089 ± 0.2 as the answer.

2) For anything else (multiplication, division, logarithms, etc.), the largest uncertainty is the quantity which is the largest percentage, and that percentage uncertainty is also the percentage uncertainty of the final answer. So $(3.5 \pm 0.2) \times (13.589 \pm 0.006) = (48 \pm 3)$ because the first uncertainty is $0.2/3.5 = 5.7\%$ (which is a much larger uncertainty than the second quantity), and 5.7% of 47.5615 is 3 (rounded off to one place). Again, note the rounding conventions: one significant figure for the uncertainty, and the measurement should appear no more accurate than the uncertainty.

You will be provided training elsewhere (not in this document) on identifying and estimating the uncertainties of measurements you make.

1 General Report Requirements

Reports for each lab activity will describe experimental methods and observations along with a discussion on analyzing the relationship between measured parameters and how this compares to the theoretical model.

These requirements apply to each of the report submissions; additional requirements specific to each lab activity are included in the lab activity descriptions.

Report Objectives

1. Describe significant elements of the experimental setup and data acquisition, with justification.
    - Your report needs to clearly document what you did and should explain why you made specific procedural design choices.
    - This methods section is supposed to help someone reproduce your results by using the same experimental setup and measurement methods.
    - You can assume the reader knows how to use a ruler, or stopwatch, etc. Focus on explaining what exactly you measured. For example, "The period was measured by timing how long the pendulum took to complete 2 full oscillations, starting and ending from when it was at the bottom of its swing." is better than "When the pendulum was at the bottom of its motion the start button was pushed on the stopwatch. The stop button was then pushed when the pendulum next returned to the bottom of its motion. The time was then multiplied by 2 to find the period." It is best if you also justify why you chose to measure the period when the pendulum is at the bottom of its motion rather than at the top or any other location (assuming that is what you did).
2. Present data acquired from experimental observations in a clear and concise manner (including uncertainties).
    - Data should be presented in graphs with uncertainty (error) bars and trend lines (the best fit of your data to some theoretical curve).
3. Discuss analysis and implications of experimental observations (as requested in each lab activity description) and compare with the mathematical model provided.
    - All reports need a discussion/analysis section where you highlight your most important results and provide any needed context for how your results should be interpreted. The context should, at minimum, reference your uncertainties. Whether your results agree with some theoretical prediction is usually one of your key findings.
    - You should clearly describe what criteria you used to reach your conclusion. For example, if you claim that your data indicates that a certain mathematical model is only a valid approximation for your pendulum for a specific range of string

lengths, you should explain what criteria you used to claim validity. One possibility is that that range of string lengths produced a period which agreed with the mathematical model within one uncertainty interval (error bar).

4. Additional objectives specific to each lab activity will be provided with the activity descriptions.

Constraints

1. You must submit the assignment by the indicated due date. The late penalty is 1% per hour. Late penalties can only be waived due to medical and other unforeseeable issues, but not if you have a big assignment in another course. Use the online petition process from the Engineering Portal.

2. Each time you submit the intermediate reports you should include the previous reports (with corrections) so that your report grows into the final report, and so the marker can quickly check any changes you made based on previous feedback. I recommend colour-coding your second report so that the marker can easily find the new material.

3. Reports will be automatically submitted to Ouriginal for review of text-similarity. It will catch copying from each other and from websites. Please do not copy! Your work is supposed to be your own, original writing. Plagiarism is a serious academic offence. If you are suspected of plagiarism you will likely have to explain the situation to the Dean of Engineering.

4. Do not include a hypothesis or list of materials

5. Additional constraints specific to each activity will be provided and must be followed.

Criteria

For all of the criteria, "more", "higher", or "greater" will be preferred.

- Appropriateness of experimental setup and methods.
- Quality and clarity of explanation and justification of experimental setup and methods.
- Appropriateness of data presentation and clarity of description of the data
- Quality of data analysis and assessment of uncertainties
- Quality and depth of discussion of the results and their implications
- Quality and clarity of writing and report style
- Incorporation of feedback from previous report submissions
- Additional criteria specific to each lab activity will be provided where applicable

2 Experimental Setup

You will build a simple pendulum and test how well the 'damped harmonic motion' model predicts the behaviour of your pendulum. Please note the emphasis – you are **not** being tested on how well you can make your actual set up represent the model, although if your pendulum is spectacularly bad (see below for examples) this will impact your results.

Pendulum Requirements

Objectives

1. Build a pendulum consisting of an adjustable length with a mass at the bottom. You can use any materials, but make sure that most of the mass is in the 'bob' at the bottom of the pendulum.

2. Conduct experiments using the pendulum to observe the relationships between characteristics of pendulum's motion with scientific rigour (repeatability).

3. Describe your pendulum design (including photos), and provide justification for your selected setup in the report for Lab 1.

Constraints

- Your pendulum must have an adjustable length.

- The pendulum should be attached to something which is 'fixed' in place in the sense that it does not move much while the pendulum swings.

- Most of the pendulum's mass should be at the bottom.

- You must include a photograph and discussion of your experimental setup.

Criteria

See criteria provided in the General Report Requirements.

What qualifies as spectacularly bad?

It includes, but is not limited to, the following: you use a heavy metal chain for a string and a Styrofoam ball for the 'mass'; your string slips frequently, changing the length of the pendulum unpredictably; your string length cannot be adjusted; the string is attached to something which moves a lot; wind or other forces (other than gravity and the string) strongly influences the pendulum's motion. If your pendulum is spectacularly bad you should fix it before the end of the semester and retake any necessary data.

This bears repeating. **You are expected to improve your experimental design and your lab report** based on feedback from the marker.

3 Lab 1: Period vs. Angle and Q factor

Goal

Your first tasks are to find how the period (T) of your pendulum depends on the angle (θ), and measure the Q (quality) factor of your pendulum. The damped harmonic oscillator model predicts no relationship between the period and the angle.

If the Q factor is much larger than 1 then it measures how many complete oscillations it takes for your system to decrease its amplitude to about 4% (technically $e^{-\pi}$) of its original amplitude (equivalent to losing about 99.8% of its initial energy).

The following assumes that your pendulum's decay is approximately exponential. If that is not the case you should discuss how to define Q with your TA or the professor.

Overview

If you find that the period does depend on the angle, and you find that your Q factor is not huge (in the 1000s), then you will need to be careful about how you measure the period. The Q factor is a measure of how quickly the amplitude decays, and if a decaying amplitude changes your period, it will be a challenge for you to accurately measure the period and Q factor as a function of the pendulum's length in part 2. Once you finish part 1, your results must be used to decide how you design your experiment for part 2.

Take data and plot it in a graph of period (y-axis) as a function of angle (x-axis). My prediction is that is should be a flat line (zero slope). You should fit it to a power series:

$$T = T_0(1 + B\theta_0 + C\theta_0^2 + \dots) \tag{4}$$

where T_0 is the period for very small oscillations. Note that you need **more** data points than the number of parameters you are trying to fit (T_0, B and C here) to get a good fit. My prediction is $B = C = 0$ (if you fit higher order terms, my prediction suggests they should all be zero). If you fit your data it will never tell you that $B = 0$, it will always give you some value. You can claim that a value is 'experimentally zero' if its value is smaller than its uncertainty. If the value is up to two times larger than its uncertainty then you can still claim it is 'consistent with zero'.

It is important that you measure your angles in radians. It is also important that you take data with starting points from $-\pi/2$ to $+\pi/2$ (i.e. -90 degrees to +90 degrees). (Actually, it is sufficient if your data only goes to, say, ± 80 degrees.)

Note that if $B \neq 0$ then something is strange with your pendulum as it is asymmetric. If you release it from the same angle on different sides you get different periods. You could design a pendulum this way but it would be highly unusual, so I expect most of you will get B is 'experimentally zero'. I make no promises about C though. **Note that you should explicitly test for an asymmetry by arbitrarily choosing one side as positive and releasing the pendulum from both positive and negative initial positions.** This data should be included in your graph, so the x-axis should have both positive and negative values. The period should always be positive.

For the rest of the activity, make sure your initial angle is small enough that C (and B) can be ignored, assuming you found that C (and B) for your setup is not consistent with zero.

Note: if you find an asymmetry in your set up, **you should modify your pendulum to get rid of the asymmetry**.

One way to measure the Q factor is to measure the period (T) and the time constant of the decay (τ), and use Equation 3. Another way is to count the number of oscillations until the amplitude is $e^{-\pi} \sim 4\%$ of the initial amplitude, and that value is Q. Alternatively, count the number of oscillations until the amplitude is $e^{-\pi/2} \sim 20\%$ and that is $Q/2$. You can similarly choose to measure $Q/3$ ($e^{-\pi/3} \sim 35\%$), $Q/4$ ($e^{-\pi/4} \sim 46\%$), etc. If your Q value is very large (over 100) you may find it tedious counting 100 oscillations to measure Q directly.

Experiment and Report Requirements

Objectives

1. Test whether the period of the pendulum is independent of the amplitude.
2. Identify asymmetry in pendulum and improve setup to eliminate this.
3. Describe how you took this data (specifically including the impact of the Q factor on your choices)
4. Graph and analyze the trends (you should fit your data to Equation (4) and plot both your data and the 'trend' line which is the best fit curve).
5. Discuss uncertainties as well as their impact on observations and analysis.
6. Provide a clear conclusion about whether your pendulum's period depends on amplitude. If you do find some dependence, you should clearly indicate what range (if any) of amplitudes are 'small enough' that the value of C can be ignored. Be clear as to what criteria you used to make a 'small enough' judgment.
7. Measure the Q factor of your pendulum using both methods (Equation (3) and counting oscillations). Note that you can use any method you wish to do this, including technologies like video cameras. Please don't spend much money on this though.
8. Present data in a graph. Remember that the x-axis is always the quantity you controlled (time or number of oscillations here) and the y-axis is always the dependent variable (the amplitude here).
9. Determine quantitatively how well your two measurements of the Q factor agree with each other. You must reference uncertainties for this.
10. Finally, you should consider how your results will impact how you take data for the rest of the experiments.

Constraints

1. Angles must be measured in radians.
2. You should explicitly test for asymmetry.
3. You should modify your pendulum to correct for any asymmetry.
4. Your write up must include a picture of your equipment, a description of which direction you measured the Q factor (I recommend the direction be in the plane of the photograph rather than in/out of the photograph), how you measured the Q factor (both ways), and your results including uncertainties and how you determined the uncertainties.

Criteria

See criteria provided in the General Report Requirements.

For this report only, a general introduction is not needed. You must still have a conclusion.

4 Lab 2: Period Versus Pendulum Length and Q Factor Versus Pendulum Length

Goal

The goal of this activity is to examine how the pendulum's length impacts both the period and the Q factor. Remember to use the results of Lab 1 to determine how best to proceed with Lab 2.

Overview

Take data and plot it for the period (y-axis) of your pendulum as a function of L (x-axis). Fit your data to the power law function

$$T = k\, L^n \tag{5}$$

where I predict you should get $k = 2$ and $n = 0.5$ to within your uncertainties.

Fit this function directly, and also plot your data with a log-log plot in which case the slope is n and the intercept tells you k. Log-log plots are particularly useful for data that obeys a power-law like Equation 5.

For each pendulum length for which you measure the period, also measure the Q factor. You can measure it using just one of the two methods you used in Lab 1. Describe which method you used and why. Fit your data to an appropriate function based on what the data looks like. Common functions to try fitting data when you don't have a theoretical prediction include linear functions, quadratic functions (like Equation 4), power law functions (like Equation 5) and exponential functions.

Remember that fitting any data to any function will always result in some reported dependence of the Q factor on length. You need to make sure that the fit parameters are larger than the associated uncertainties before you make a final decision on whether (and how) Q factor depends on pendulum length.

Requirements

Objectives

1. Discuss whether equation (2) is consistent or inconsistent with your results.
2. Discuss uncertainties as well as their impact on observations and analysis.
3. Determine what effect, if any, that the pendulum length has on the Q factor.
4. Provide an introduction and conclusion to your report.

Constraints

1. The discussion about how you did this should be informed by the results of the first lab (specifically the Q factor and whether C was important).
2. Period vs. length data must be plotted and fit to the power law function in equation (2).
3. You should plot your data on log axes as well as regular axes (same data, 2 graphs).
4. You should explain which method of determining the Q factor you used, and why.
5. You must clearly explain whether or not you find that the Q factor does depend on the pendulum length. This discussion must reference your uncertainties.

Criteria

See criteria provided in the General Report Requirements.

5 Final Report

Goal

In terms of your overall report, remember that the goal of this project was to build a pendulum and test how well it was modelled by a specific mathematical theory which you were provided. This should be the focus of your paper. Everything you write should be aimed at **quantitatively** assessing how well the theory models your equipment.

You will submit your final report, **with all changes and improvements as suggested by your TA**, near the end of the semester.

Overview

Think of the first two reports as rough drafts and the third report as the final product. This report should include an introduction and a conclusion, as well as the content from the reports submitted previously.

The introduction to your final report should include a brief summary of your results. In a scientific paper, the introduction might be the only thing most people read, so it needs to catch their attention. Results (with uncertainty as appropriate) are the standard way of getting the reader's attention. The typical scientific paper starts with "We measured this value with high precision using this kind of setup. Here's why that should excite you." Granted a pendulum doesn't have much excitement value in modern science, but you should nonetheless try to emulate that introduction formula. I suggest writing your introduction last, after even your conclusion (which is probably good advice for everything you ever write at university). This will help make sure that your introduction and conclusion agree with each other and focus on the same issues. Papers where the introduction and conclusion disagree or discuss different topics are confusing to read.

The conclusion should highlight the key takeaways from the results and discussion sections of the report. The typical scientific paper will state what the key findings were, their implications on the subject of the paper, and how this may influence future work in the field.

Instead of future work in the field, you should describe what the largest source of uncertainty was and how you could reduce it in future work.

Final Report Requirements

Objectives

1. Discuss how well the 'damped harmonic oscillator' models your experimental setup using quantitative experimental observations. Clearly describe any limitations of the model's applicability to your pendulum you discovered.
2. Provide an introduction and conclusion to the report.
3. Improve your experimental setup and methods according to feedback and/or any new ideas you may have. Include an overview of changes with justification.

Constraints

1. While you should talk with your peers, your reports must be done by yourself. Your data is your own, your analysis and graphs are your own, and the writing must be your own.
2. Your final report should include an introduction and conclusion, as well as all the data and methods that you submitted previously.
3. Any feedback you got from the first three reports must be incorporated by this stage if you want a good mark - the expectations at this step will be higher than they were before. **This specifically includes the expectation that you take new data if you received feedback about your data.** Even if you did not get such feedback, you are free to redo your data collection in light of new ideas you have.

Criteria

- Quality, clarity, and rigour of data analysis as well as the corresponding discussion comparing experiment and theory.
- Appropriateness and quality of the introduction and conclusion of the report.
- See criteria provided in the General Report Requirements.