Guidelines for Writing Lab Reports

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1. Overview

Lab reports are your first foray into scientific and technical communication. In all aspects (content, organization, and writing style) these reports mimic actual published scientific papers. Scientific papers are narrative essays organized into sections so that the desired information can easily be found. Each section of the lab report explains part of the scientific method. Depending on the experiment, your lab reports should typically be 5-10 pages long, including figures and tables. However, there is no minimum/maximum length requirement. The length guidelines listed in this document are to help you determine whether or not you have included enough detail.

2. Writing in Groups

Real scientific papers are almost always written in collaborations with multiple authors. The goal of group lab reports is twofold. Firstly, writing in groups allows you to focus a higher percentage of your effort on individual sections of the lab report, thus creating a stronger overall product. Secondly, writing in groups allows you to practice proof-reading and editing your partner's work.

Writing in groups is voluntary. You may always complete the lab report on your own. However, on average, students who have taken the time to write and proof-read in groups tend to write better reports, catch more calculation errors, and receive higher grades.

Group lab reports should only be completed by groups of 2 or 3 students, maximum. All students writing the group lab report must be working in the same lab group, using the same data.

You are required to split the writing work as evenly as possible. Some students choose to sit down next to their partners and write in real-time. Other groups split up the work and write individually, edit each other's writing, and then recombine the sections. If you do choose to split up the work, then to receive full credit, you are required to indicate the names of the contributors at the beginning of each section of the lab report:

       Primary Author: _____
- o The primary author is the person who wrote the majority of the text in this section of the lab report.
- o You cannot be the primary author for the same sections of the lab report two reports in a row.

       Editing Author: _____
- o The editing author is the person who took primary responsibility for proof-reading and editing the primary author's work.
- o You may have two editing authors, if desired, in groups of three.

3. Sections of the Lab Report

The lab report is broken down into four sections: Introduction, Methods, Data Analysis, and Discussion. Each section must include very specific content, as described below.

3.1 Introduction

The typical length of an introduction is a few paragraphs to one page. The introduction must convey three main ideas:
- Explain the motivation for your experiment. Why is your scientific question important?
- Explain all relevant background information about your scientific question and your experiment. You might choose to discuss physical principles discussed in lecture, or do some background research related to the topic of your experiment.
- A clear statement of your scientific question and the goal of your experiment.

3.2 Methods

The typical length of the methods section is 2 – 3 pages. This section describes **what** you did in your experiment and **why** you did it. Explain your lab procedure in enough detail to be reproduced by another student.

One common pitfall in the methods section is to explain every thought you had, and every wrong turn your group made in the course of the experiment. The methods section is not meant to be a journal, but rather an organized description of the final, successful experiment.

In the methods section, you should also display your raw data (i.e., the numerical **measurements** you made in your experiment) and the uncertainties on your measurements. Here, "raw" means you have not performed any calculations with your data. Data should be displayed either in figures (histograms or scatter plots) or tables, whichever you think conveys the information the clearest. Do not show the same values in both a figure and a table; pick one or the other.

Organization: The methods section should be organized **in the following order**:
  (1) 1-2 sentences providing a general overview of the experiment. This may include a labeled diagram of your experimental set-up. (However, in some cases, the diagram may be more appropriately located near the procedure; see (3) below.)
  (2) Any necessary derivations or mathematical equations important to your experiment.
       a. The Methods section should contain derivations involving *variables only*; once you start performing calculations with your numerical data, those calculations belong in the Data Analysis section.
       b. When you show a derivation, you must explain **what** you are doing in words, and embed the equations into your sentences. You must also explain **why** you chose to perform each step of the derivation.
  (3) A detailed procedure
       a. Show a diagram of your experiment, if not already shown. Several diagrams may be necessary.
       b. Identify the equipment and computing tools you used. However, **never** list the equipment in one long sentence; just identify pieces of equipment as you go through your description of the procedure.
       c. Explain your data collection methods.
       d. Scientifically explain the reasoning behind the procedure you created.
              For example: *We used an air track in order to reduce friction.*
  (4) Numerical data (including tables, plots, and measurement uncertainties)

3.3 Data Analysis

The typical length of the Data Analysis section is 2 – 3 pages, depending on the complexity of the analysis and number of tables and figures. This is the section in which you perform all

calculations with your data, determine your experimental uncertainties, and show mathematical fits on relevant plots.

When you show your calculations, you must explain what you are doing in words and embed the equations into your sentences. You must also explain **why** you are performing a particular calculation.

If you used a plot or graph to help you analyze your data, you must **show** it and **describe** it in this section. You may have used either LoggerPro or Excel to fit a line to your data, and the results of that fit are considered "analysis", rather than "raw data", because you made a conscious decision to model your data in a certain way. If several plots of the same type are used (for example, for multiple trials of an experiment) then show one plot as an example.

The final thing that belongs in the data analysis section is your error analysis, i.e., calculations of your experimental uncertainties. You should have listed all measurement uncertainties in your methods section, and in your data analysis section you propagate these errors into uncertainties in your final result. You should conclude the error analysis section by calculating your percent error, and (if applicable) a percent difference from the known value of the quantity you are trying to measure. A detailed document explaining how to calculate your errors is available, entitled "Understanding Experimental Error". This document is available on Canvas in the Lab folder.

3.4 Discussion

The typical length of the discussion section is 1 – 2 pages. This is the section where you interpret your results, answer your initial scientific question, and discuss everything else relevant to understanding your experiment. You may want to consider the following questions as you write your discussion section:
- Is your data sufficient to answer your scientific question?
- Are there any other interpretations of your data?
- What sources of bias were you unable to remove from your data?

You also need to discuss the sources of uncertainty in your data. Regardless of whether you got a very good result, or whether your result has something obviously wrong with it, there are **always** sources of error in your experiment. When considering sources of error, you may refer back to the handout from lab class about different types of experimental error. When writing this section, you may want to consider the following questions:
- Are your uncertainties small enough to answer your scientific question?
- Of the several different sources of error in your experiment, which do you think is the largest or most important?
- How might future experiments minimize these sources of uncertainty?
- Is your experiment biased in any way? If so, how would you improve this in future experiments?

- Did anything else come up during the experiment that may have affected your data in an unanticipated way?

Finally, you must relate your findings to the bigger picture. Do your results make sense with the experimental results of other scientists and/or prevailing scientific theory? If not, what might be the cause? How do you reconcile the difference? If your results do not agree with prevailing scientific theory, you must take extra care when writing this section to demonstrate that you understand what caused the discrepancy.

4. Figures & Tables

Figures and tables are the primary way that you help your reader visualize your data. You must include figures and tables in your lab report, but the exact type and placement is up to you.

A figure refers to an image (such as a picture of your experimental setup) or a plot (scatter plot or histogram). A table is a labeled chart that displays multiple numerical values in a condensed and organized manner. Examples of figures and tables can be seen in the sample student lab report.

Both figures and tables are required to have **captions** below them. Captions are usually several sentences to 1 paragraph in length. They serve two functions:
- Captions explain what is being plotted in the figure. They should include details of all data points and curve fits, and explain the axis labels, legend, and any other plot details.
- Captions explain to the reader the purpose of showing the figure. Describe what information the reader should take away from the figure, and (if applicable) the role your figure played in the analysis of your data.
- Captions are the one place in the lab report where repetition is okay. In general, you want the information in your caption to also be present in the body text of your report; you may paraphrase (this is ideal) or copy word-for-word from your caption.

5. Rules for Formatting

The formatting rules described below are modeled after guidelines in actual scientific journals.

5.1 Formatting the overall document

The main body of the lab report should be written in paragraph form, single-spaced, with size 12 font (Arial or Times), and 1-inch margins. Never use bullet points in the lab report.

The sections are titled and numbered in order, and organized just as the sections in this document are. If you have any subsections, use a decimal point followed by a second number to label the subsection. If, for example, there are two mini-experiments that comprise your lab,

then you should discuss the procedure of both experiments in different subsections of your methods section. An example of how you would label sections is as follows:

1. Introduction
2. Methods
    2.1 First experiment: Water running through a pipe
    2.2 Second experiment: Light from the Sun
3. Data Analysis
    3.1 Calculation of flux of water
    3.2 Calculation of flux of light
    3.3 Error Analysis
4. Discussion

You may refer to section numbers in the body of the text, for example:

> Table 2 shows the acceleration found in each trial, along with the mean acceleration. Calculations of the mean acceleration and its uncertainty may be found in Section 3.3.

Equations, figures, and tables are interspersed between sentences and paragraphs so that they can be viewed chronologically as the report is read. Figures and tables should always be mentioned in the body paragraphs, so that the reader knows they need to pause in their reading and go look at the figure or table.

5.2 Formatting Figures, Tables, and Captions

Figures and tables should always appear at the top or bottom of the page where they are mentioned in the body paragraphs. If for some reason this is impossible, they should come as soon as possible on the top or bottom of the next page. If the figure or table is at the bottom of a page, the entire caption underneath needs to fit on the page. The figure or table itself should be center-justified, and the caption below should be left-justified. Figures, tables, and their captions should always take up the whole width of the page, and should not have text from the body paragraphs "wrapped" around them.

Tables and figures should all be numbered in chronological order as they appear in the text. If you have three figures and two tables, they should be called: Figure 1, Figure 2, Figure 3, Table 1, and Table 2. The name of the figure or table should be indicated at the beginning of the caption.

5.2.1 Figures

If your figure is an image or diagram, make sure it is properly labeled.

If your figure is a plot or graph, it must have the following properties:
- Labeled horizontal and vertical axes, including units in brackets [] or parentheses ().
- No title.
- No legend, unless multiples types of data are being plotted simultaneously.
- Legible fonts.
- Data points representing measured values.
- Curve fits to data, if applicable.

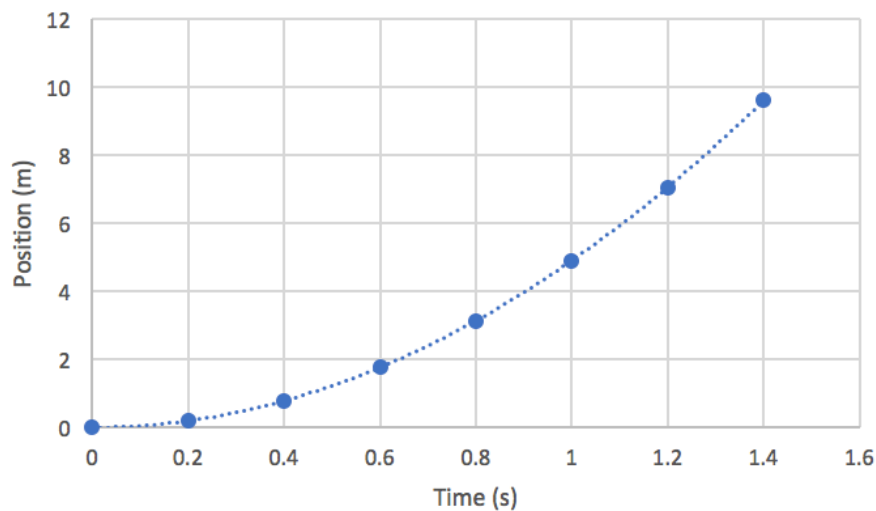An example of a properly formatted plot is shown on the next page.

Figure 1 – Here we show position vs. time for the first trial of our experiment. All trials had plots of similar shape. As the ball falls, it accelerates due to the force of gravity, as can be seen in the curvature of the path that the data points follow. For each trial, we fit a parabola to the position vs. time data to model the change in position of the ball as it fell, and used the coefficients of the fit to measure g, *the acceleration due to gravity.*

5.2.2 Tables

Tables should have labeled headings with units included in the heading. Both measured values and corresponding uncertainties must be listed in the table. If the uncertainties on several values are the same, you may simply quote the uncertainty in the heading. All values in a table must be rounded to the correct number of significant figures. Two examples of properly formatted tables are shown below.

Time (s)	Position (m)

(± 0.05 s)	(± 0.1 m)
0.0	0.0
0.2	0.2
0.4	0.8
0.6	1.8
0.8	3.1
1.0	4.9
1.2	7.0
1.4	9.6

Table 1 – Here we show the position vs. time data for the first trial of our experiment. Time is measured to a precision of 0.05 s and position is measured to a precision of 0.1 m. As the ball falls, it accelerates due to the force of gravity and the position increases proportionally as $\frac{1}{2}at^2$.

	Acceleration (m/s²) (± 0.1 m/s²)
Trial 1	8.8
Trial 2	9.7
Trial 3	6.1
Trial 4	10.3
Trial 5	9.3
Trial 6	9.7
Trial 7	10.9
Trial 8	9.9
Mean	**9.3 ± 0.5 m/s²**

Table 2 – Here we show the acceleration of the falling ball as calculated in each of the eight trials, along with the mean acceleration of all trials. The error in individual acceleration measurements is 0.1 m/s², and the error in the mean is 0.5 m/s².

5.2.3 Captions

Caption text should appear directly below the table or figure, and should be indicated using *italics* font. Caption text should not be smaller than 12pt. Captions must fit completely on the page below the figure; if the caption runs onto the next page, reformat your body paragraphs to allow the figure to be moved up on the page.

5.3 Formatting Equations

You must show equations in your lab report. To display equations, please use a typed format (for example, Microsoft Equation Editor, which is available inside Microsoft Word). To insert an equation into a paragraph of text, simply hit enter, type the equation (centered) on a new line,

and then hit enter again and continue with your sentence. Equations are treated just like words in a sentence, and if the equation comes at the end of a sentence, you must follow it with a period.

When typing in equations, make sure that your entire equation is typed in "equation mode", or else there might be mismatch with the fonts. Equation mode should naturally format variables correctly. When you add numbers and units, you must add spaces between numerical values and their unit, and un-italicize the units manually.

An example of properly formatted equations is shown on the next page.

In order to calculate the mass m, we used Newton's 2nd Law

$$F = ma$$

and solved for the mass

$$m = \frac{F}{a}.$$

When we inputted the average force (F = 25.0 N) and the average acceleration (a = 3.4 m/s) we obtained

$$m = \frac{F}{a} = \frac{25.0 \text{ N}}{3.4 \text{ m/s}} = 7.4 \text{ kg}.$$

6. Writing Style

Scientific writing has its own unique style in the **tone** of the writing. It may take some time to get used to the new style, but you will become more adept at it the more lab reports you write. Some general tips are provided below.

6.1 Tone

The lab report should be aimed at one of your peers. Imagine you are sending your report to a physics student at another college in order to explain your experiment to them. You may assume they have the basic knowledge of physics you have received in class, but are not familiar with the experiment you did in lab.

Scientific writing tends to be very precise, which sometimes requires many words and/or sentences to explain a concept. Because so much precision is required, your writing should not be overly "flowery" or metaphorical, and you should waste words repeating ideas that have already been explained. Make sentences simple and to the point. You want to be **thorough** – do not leave out important information – but also as **concise** as possible. Lab reports have no required length; do not add "fluff" (irrelevant or repetitive information) to artificially increase the length of your report.

As experiments are always performed in groups, always use the pronoun "we" when referring to what your group did in the experiment. Never name individual group members or write "you" or "I".

Your report should be written in a mixture of past tense and present tense only. (Future tense is never used.) Past tense is used to describe actions you performed as part of the experiment. For example:
> We **_measured_** the acceleration ten times and then **_calculated_** the mean value.

Present tense is used to describe facts (physics principles, equipment, data, etc.). For example:
> Because the origin of our coordinate system **_is_** at the top of the building, the
> height h **_is_** equivalent to the distance that we dropped the ball.

The tone of the lab report should be professional. Do not talk about "the lab" as if you are a student in class; write as if you are a professional physicist reporting your results.

Do not use:	Incorrect	Correct
• abbreviations	_vel._	_velocity_
• contractions	_doesn't_	_does not_
• colloquial language	(_see example sentences below_)	

** Colloquial language: words used in ordinary or familiar conversation, but not in written text.

Do not use chatty, colloquial, or funny language in a lab report. Below is an excerpt from a student report. The last part of the sentence (indicated in bold) should be changed in order to be more professional and more precise.

Original:
> "The manner in which we collected data was not inherently flawed (i.e., measuring distance from the cannon to the carbon paper, and then adding that to distance of the marks on the paper); **however, we were nothing more than five men with a measuring tape.**"

Better:
> "The manner in which we collected data was not inherently flawed (i.e., measuring distance from the cannon to the carbon paper, and then adding that to distance of the marks on the paper); **however, the precision of our measurements is limited by the size of the tick marks on the measuring tape and how steadily we can hold the tape.**"

6.2 Grammar and Word Choice Tips

This section lists common errors in lab reports, and indicates how to avoid them.

- **Stating your scientific question.** In the introduction, you are required to state the goal of your experiment. Do not state it in the form of a question. For example:
  - Bad: *What is the acceleration due to gravity?*
  - Good: *In this experiment, we aim to determine the acceleration due to gravity.*
- **The word "data" is plural.** It may seem unintuitive, but it's true. If you need to refer to a single measurement on a plot, call it a "value" or "measurement" or "data point". Here are examples of correct usage:
  - *Our data show that…*
  - *These data are inaccurate because...*
  - *We collected data for 1 minute.*
  - *The first data point on the plot is an outlier because…*
- **"Average" is an ambiguous term.** If you calculated the mean, say "mean", not "average". Average may refer to either the mean, median, or mode.
- **Use the correct verb!** Don't say *"We got a value of 20 m."* Not only is *"got"* too colloquial, it is also very vague. Use a more descriptive verb than *"got"*. Each of the verbs used below carry different meanings:
  - *We <u>measured</u> a value of 20 m.*
  - *We <u>calculated</u> a value of 20 m.*
  - *We <u>inferred</u> a value of 20 m.*
- **Avoid the term "plug in".** Yes, we <u>say</u> it all the time, but it is a colloquial term that should never be <u>written</u>.
  - Bad: *We <u>plugged in</u> the expression for ρ into Equation 1.*
  - Good: *We <u>substituted</u> the expression for ρ into Equation 1.*
  - Good: *We <u>inputted</u> the expression for ρ into Equation 1.*
- **Avoid the words "lab" and "lab partner".** Don't use <u>any</u> language that indicates that this experiment is part of a classroom activity, or that you were "supposed to" measure something. Write about your experiment in a professional manner, as if you were publishing new experimental research, not performing an assignment for a class.
- **Avoid the phrase "need to".** It is completely unnecessary.
  - Bad: *We <u>needed to</u> measure the mass using a scale.*
  - Good: *We <u>measured</u> the mass using a scale.*

7. Grading Rubric

The lab report is graded out of 20 points, as shown in the rubric on the next page. A score of 5-4-3-2-1 on an individual category indicates a grade of A-B-C-D-F. The overall lab letter grade also follows this system, and you can understand how your final numerical score translates into a letter grade by looking the box labeled *Interpreting your Lab Score*.

Lab Report Grading Rubric

Clarity of Writing	1	2	3	4	5
Mathematical Analysis	1	2	3	4	5
Content	1	2	3	4	5
Organization & Professional Appearance	1	2	3	4	5

Total: _____ /20

Explanation of Categories:

A good lab report will have the following characteristics:

Clarity of Writing
- Correct spelling, grammar, and word usage
- Professional language used
- Clear sentence structure and flow

Mathematical Analysis
- Equations used correctly
- Accurate estimates of uncertainties
- Accurate graphs and tables
- No numerical mistakes

Content
- All required sections are present
- All necessary content is present within each section
- The lab procedure was accurately followed
- The student demonstrates a clear understanding of the purpose of the lab

Organization and Professional Appearance
- All required sections of the lab write-up are clearly indicated
- Content within each section is organized and easy to follow
- Lab report is neat, professional looking, and visually appealing
- Any hand-written equations or diagrams look professional
- Typed, 12 pt font used, figures have captions and are in-line with text

Interpreting your Lab Score:

A	18 - 20
B	14 - 17
C	10 - 13
D	6 - 9
F	0 - 5

8. Sample Lab Report

The following pages show a sample lab report turned in by a past student. This report earned an A, so you may use it to get an idea of the general format of **equations, figures, and tables**, the **tone of the writing**, and the **overall quality** of lab report that is expected.

However, this lab report is not perfect. For example, it was not organized correctly according to the guidelines presented in Section 3, especially in the Methods and Data Analysis section. Use it as a template for formatting only.

Sample Lab Report

1| INTRODUCTION

The term "phase" in calorimetry refers to a specific state of matter such as solid, liquid, or gas. A transition from one phase to another is called a phase change or a phase transition. For a given pressure, a phase change of a substance occurs at a constant temperature by a gain or loss of heat. A common example is the melting of ice; at an atmospheric pressure of 1 atm, the addition of heat to ice at 0°C melts it into its liquid form, but does not increase the temperature of its composition: the purpose of adding heat to a substance during its phase transition is to change its phase, but not its temperature.

The latent heat of fusion of a substance, denoted as L_f, is the energy required to melt a unit mass of the substance. Under normal atmospheric pressure conditions, melting 1 kg of ice at 0°C to the equivalent of liquid water requires 3.35×10^5 J of energy, so the latent heat of fusion for H_2O is 3.34×10^5 J/kg. In general, we can find the energy required to melt a mass of any material by relating its latent heat of fusion L_f with the equation below:

$$Q_f = mL_f.$$

It is possible to determine the value of L_f by measuring the amount of energy Q_f required to melt a mass m of a solid substance when its temperature remains at its melting point. Q_f is often determined by the concept of the conservation of energy: in a thermally isolated system—one in which no (or negligible) heat is lost to its surroundings—the sum of the heat lost and gained by the system must remain at zero. For example, pouring warm water on ice in an insulated container results in equal magnitudes of heat lost by warm water and gained by ice. Finding Q_f, then, would be possible by combinations of heat transfer expressions in the general concept of

$$Q_{\text{lost}} + Q_{\text{gained}} = 0$$

where, under temperature changes of a substance, energy change in a substance would take the form of $Q = mc\Delta T$, and under phase changes of a substance, the change would take the general form of $Q = \pm mL$ (positive for heat gain, and negative for heat loss). In this lab, we found the Q_f value of water by the conservation of energy and compared various Q_f values based on melted masses of ice, which allowed us to determine the value of L_f for ice-water transitions.

Author: Anonymous; Editor: Anonymous

2| METHODS

To find an experimental value for the heat of fusion of water, we mixed ice and hot water in a calorimeter and observed the mixture equilibrating. We obtained two calorimeters and determined the mass of their inner containers (which was made of aluminum) while simultaneously heating a beaker of water on a hot plate to around $350\,\text{k}$ ($80°\text{C}$).

We added ice to one of the aluminum containers (blue in **Figure 1**) and recorded the total mass of the combination; to find the mass of ice m_I added to the container, we subtracted the mass of the container from the measured total mass. We poured hot water into another container (red in **Figure 1**) and covered the container with a well-insulated cap of known mass; similarly, we found the mass of water m_w by subtracting the total mass of the cap and container. We placed the containers into to their calorimeters while inserting a temperature probe into each. Then, we stirred each substance until both reached equilibrium with their aluminum container, and determined the temperature of equilibrium when the temperature reading from the probe did not change for around $20\,s$ (left panel of **Figure 1**). We recorded the temperature of the initial state of each substance—T_i for ice and T_w for water—and poured the warm water into the container of ice (middle panel of **Figure 1**). Lastly, we used the probe in the ice container to mix the substance, recording the temperature T_f of the substances after they reached thermal equilibrium (right panel of **Figure 1**).

We repeated this process for four other trials shown in **Table 1**. Each measurement listed in **Table 1** had an error related to the precision of the used measuring instrument. We found that the inner container of the calorimeter we used for Trials 2, 3, 4, and 5 had a mass of $0.05529\,\text{kg}$. In Trial 1, we poured ice into water instead, and used a calorimeter of an inner-layer mass of $0.05563\,\text{kg}$.
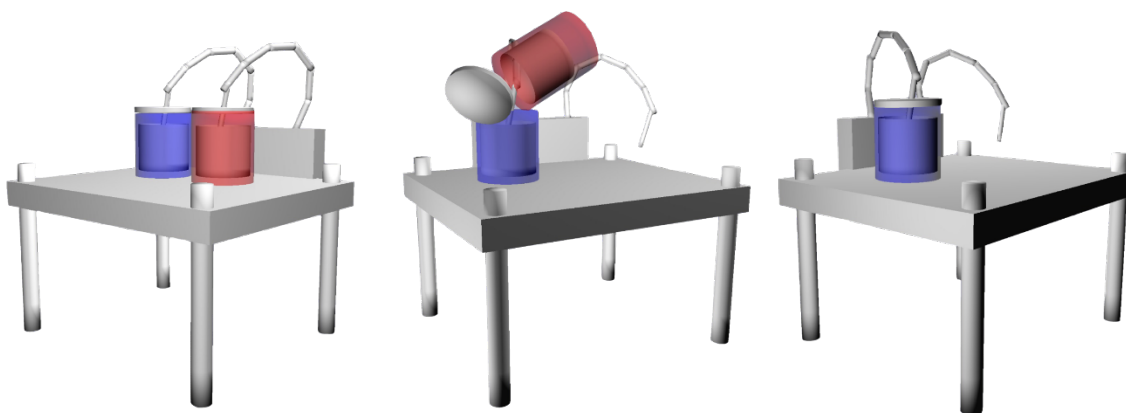

Figure 1: The experimenting process; the red container represents the calorimeter that initially contained water, and the blue container represents the one that contained ice.

	m_I (kg) $(\pm 5 \times 10^{-6}$ kg)	m_w (kg) $(\pm 5 \times 10^{-6}$ kg)	T_w (K) $(\pm 5 \times 10^{-2}$ K)	T_i (K) $(\pm 5 \times 10^{-2}$ K)	T_f (K) $(\pm 5 \times 10^{-2}$ K)
Trial 1	0.14950	0.26455	338.0	273.3	289.2
Trial 2	0.16883	0.28122	338.7	273.5	286.4
Trial 3	0.13618	0.32982	343.5	273.2	286.3
Trial 4	0.14061	0.35691	346.1	273.2	300.8
Trial 5	0.14506	0.35420	345.7	273.2	298.7

Table 1: Data for the determination of the latent heat of fusion for H₂O. In Trial 1, we added ice to water instead of water to ice.

Author: Anonymous; Editor: Anonymous

3| DATA ANALYSIS

To determine the latent heat of fusion L_f of H₂O, we related L_f to the amount of energy Q_f that was required to melt a mass of ice. To find Q_f, we noted that the net heat transfer within the thermally isolated system of our apparatus was

$$Q_\text{net} = 0.$$

The energy transferred to the ice was

$$Q_\text{ice} = Q_f + m_I c_\text{w}(T_f - T_i)$$

where c_w was the specific heat of water (melted ice). The energy transfer to the calorimeter was

$$Q_\text{cal} = m_\text{cal} c_\text{Al}(T_f - T_i)$$

where m_cal was the mass of the inner aluminum container of the calorimeter (which experienced insulation from its surroundings by air) and c_Al was the specific heat of the aluminum. The energy transfer to water was,

$$Q_\text{water} = m_\text{w} c_\text{w}(T_f - T_w)$$

where c_w was the specific heat of water. The total energy transfer was thus

$$Q_{ice} + Q_{cal} + Q_{water} = Q_f + m_I c_\text{w}(T_f - T_i) + m_\text{cal} c_\text{Al}(T_f - T_i) + m_\text{w} c_\text{w}(T_f - T_w) = 0.$$

Solving for Q_f, we had

$$Q_f = -m_I c_w (T_f - T_i) - m_{cal} c_{Al} (T_f - T_i) - m_w c_w (T_f - T_w),$$

which was the energy required for the melting of a mass of ice m_I. In the process of melting, H_2O molecules gained energy, so Q_f was positive. It followed that

$$Q_f = +m_I L_f$$

so that

$$L_f = \frac{Q_f}{m_I}.$$

Table 2 shows calculated Q_f and L_f values for each trial.

	Q_f (J)	L_f (J/kg)
Trial 1	46603.7 ± 690.4	311720 ± 4620
Trial 2	51851.3 ± 736.0	307110 ± 4360
Trial 3	51085.0 ± 749.1	375120 ± 5500
Trial 4	50094.4 ± 781.7	356250 ± 5560
Trial 5	52970.5 ± 784.7	365150 ± 5410

Table 2: Calculated Q_f and L_f values for each trial.

The mean L_f was 343070 J/kg $\pm$ 14080 J/kg, a 2.72 % difference from the accepted value of $L_f = 334000$ J/kg. The percent error for our L_f experimental value was 4.10 %.

Author: Anonymous; Editor: Anonymous

4| ERROR ANALYSIS

We took partial derivatives of the Q_f expression with respect to variables that carried inexact values.

$$\frac{\partial Q_f}{\partial m_I} = -c_w (T_f - T_i)$$

$$\frac{\partial Q_f}{\partial m_{cal}} = -c_{Al} (T_f - T_i)$$

$$\frac{\partial Q_f}{\partial m_w} = -c_w (T_f - T_w)$$

Assuming an error of 5 J/kg · k for all specific heats, we performed partial derivatives on our Q_f expressions with respect to specific heats.

$$\frac{\partial Q_f}{\partial c_w} = -m_I(T_f - T_i) - m_w(T_f - T_w)$$

$$\frac{\partial Q_f}{\partial c_{Al}} = -m_{cal}(T_f - T_i).$$

For temperature values,

$$\frac{\partial Q_f}{\partial T_f} = -(m_I c_w + m_{cal} c_{Al} + m_w c_w)$$

$$\frac{\partial Q_f}{\partial T_i} = m_I c_w + m_{cal} c_{Al}$$

$$\frac{\partial Q_f}{\partial T_w} = m_w c_w.$$

We found the error e_Q of the Q_f value of a single trial by

$$e_Q =$$

$$\sqrt{e_{m_I}\left(\frac{\partial Q_f}{\partial m_I}\right)^2 + e\left(\frac{\partial Q_f}{\partial m_{cal}}\right)^2 + e_{m_w}\left(\frac{\partial Q_f}{\partial m_w}\right)^2 + e_{c_w}\left(\frac{\partial Q_f}{\partial c_w}\right)^2 + e_{c_{Al}}\left(\frac{\partial Q_f}{\partial c_{Al}}\right)^2 + e_{T_f}\left(\frac{\partial Q_f}{\partial T_f}\right)^2 + e_{T_i}\left(\frac{\partial Q_f}{\partial T_i}\right)^2 + e_{T_w}\left(\frac{\partial Q_f}{\partial T_w}\right)^2}$$

The error of the calculated value of L_f for a single trial was thus

$$e_{L_f} = L_f\sqrt{\left(\frac{e_Q}{Q_f}\right)^2 + \left(\frac{e_{m_I}}{m_I}\right)^2}.$$

To find the error in the mean of our results, we used the standard deviation σ between the five trials to find the error of

$$e_{L_f-mean} = \frac{\sigma}{\sqrt{5}}.$$

Then, we used the following method to calculate percent error, a quantitative measure of precision, for the final mean value:

$$\% \text{ error} = \frac{\text{error}}{\text{mean value}} * 100\% = \frac{e_{L_f-mean}}{\overline{L_f}} * 100\% = 4.10\%.$$

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5| DISCUSSION

Results show that our calculated value of L_f for H_2O, which carries a 4.10% error, had a 2.72% difference from its accepted value. The process of experimenting required trial and error to find results within $\sim 12.5\%$ difference from the accepted L_f. We changed methods during the experiment for improvements: in our recorded first trial, we poured ice into hot water, but quickly realized that excess ice remained in its container (an insulated calorimeter). This meant that the mass of ice that we weighed differed from the actual amount that the experiment consumed. On later trials (2, 3, 4, and 5), we instead poured hot water into the ice calorimeter to minimize such inaccuracies.

We noticed that, in multiple trials, $T_i > 273.15$ k. The amount of time required to weigh the ice and wait for it to reach thermal equilibrium with its container might have allowed ice to slowly melt due to gains in energy from its higher-temperature metal container. This meant that less energy needed to melt all the ice, since some of the weighed ice was already in liquid form. Additionally, after measuring the initial temperature of heated water in its red calorimeter (**Figure 1**) container, water might have cooled after passing through air when we poured it into the blue calorimeter (**Figure 1**). This might have made our recorded initial temperature of water inaccurately higher than its actual temperature. Furthermore, we found that it was difficult to obtain a precise measurement of the mass of warm water, since warm water constantly evaporated. These three factors were main contributions to inaccuracies in our data.

The equations and theories that we used worked reasonably to approximate the value of L_f, but additionally finding the temperature lost to the temperature probe would improve the accuracy of our result. Experimentally, using a tube to transfer warm water (to minimize loss of heat during the transfer process) would increase the accuracy of the recorded initial temperature of warm water. Additionally, cooling the ice container until adding warm water would reduce the inaccuracies in our recorded masses of ice. Nevertheless, with a final mean L_f value within five percent error in precision and five percent difference from the accepted value, the methods of this experiment have succeeded in finding an accurate and precise value of the latent heat of fusion for H_2O.

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