Introduction to the Teaching Laboratory
M Eng Materials Science, Prelims and Part I
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This document introduces the teaching laboratories and explains the rationale behind practical teaching and assessment in the laboratory. Your *Course Handbook* gives details on policies and processes, and the definitive guide to assessment is given in the *Examinations Regulations* for your year.

1. Purpose of teaching laboratories

Materials Science is predominantly an applied science and much of the research in Materials Science is experimental in nature. It is therefore important that you learn appropriate experimental skills as part of your degree. This involves handling samples and equipment in the laboratory, reading and assimilating briefing documents, time management, working in groups, and meeting deadlines in writing and submitting reports.

We hope you will find the teaching laboratory experiments interesting and enjoyable, and that they help reinforce your learning in other parts of the course.

2. Attendance and timing

The marks arising from teaching laboratory assessments form part of the overall year marks and are examinable coursework. In Prelims (Year 1) this means that the laboratory marks form part of your overall Prelims mark.

Second-year marks count towards the overall Part I mark and thus the overall degree classification. Because the practical marks are part of the Prelims or overall degree assessment, **attendance to all practicals and submission of laboratory notebooks and reports are compulsory.** You need to sign in and out of the teaching laboratory on each afternoon of attendance. You must attend the briefing by the Senior Demonstrator. *You must get your laboratory notebook time and date stamped at the beginning and end of each practical and not start the practical until you have received the briefing and had your laboratory notebook stamped*.

It is expected that you attend labs for each full afternoon the practical is scheduled and you will need to secure permission if you need to leave early.

It is recognised that sometimes ill-health or other personal circumstances may cause a difficulty in attending a specific laboratory session. If you are in the first week of a particular experiment, it may be possible to accommodate you in the following week. If you miss a scheduled session in the teaching laboratory your tutor will be informed. A valid reason for absence can be presented following the process described in the Course Handbook (Section 10.3).

The schedule of practical labs during the whole academic year is:

First Year

Term	Prac	Practical Title	Week (days)
MT	1P1a	Intro to Computing	1 (T-F)
	1P1b	Intro to Microscopy	2 (Th-F)
	1P2	Data Acquisition and Processing	3, 4 (Th-F)
	1P3	Youngs Modulus	5, 6 (Th-F)
	1P4	Metallography	7, 8 (Th-F)
HT	1P5	Bubble Raft	1, 2 (Th-F)
	1P6	Thermanl Analysis	3, 4 (Th-F)
	1P7	Electrode Potentials	5, 6 (Th-F)
	1P8	Polymers	7, 8 (Th-F)
TT	1P9	Energy Levels & Band Gaps	1, 2 (Th-F)
	1P10	Fabrication and Testing	1-4 (Th-F)

Second Year

Term	Prac	Practical Title	Week (days)
MT	2P1	Materials Selection	1, 2 (M-W)
	2P2	Steels	3, 4 (M-W)
	2P3	Extrusion	5, 6 (M-W)
	2P4	Casting	7, 8 (M-W)
HT	2P5	Mech Props Polymers	1, 2 (M-W)
	2P6	Dislocations	3, 4 (M-W)
	2P7	Corrosion	5, 6 (M-W)
	2P8	Diffusion	7, 8 (M-W)
TT	2P9	XRD Detective	1-4, 7, 8 (M-Th)
	2P10	SEM & Fracture	1-4, 7, 8 (M-Th)
	2P11	TEM	1-4, 7, 8 (M-Th)
	2P12	Semiconductor Devices	5, 6 (M-W)

In Year 1, each practical takes two afternoons on Thursday and Friday.

Year 2 practicals are longer and are conducted on Monday, Tuesday and Wednesday.

You will normally work in groups of 3, with several groups doing the experimental in parallel.

The list of practicals for each term and your allocation to a particular week and group can be found on the department website. Reading briefing documents is a common and necessary activity for scientists and you should read through the instruction scripts in advance of the practical (they are all available on the website at www.materials.ox.ac.uk/teaching/ug/ugpracticals.html).

If you have any doubts, please ask the Senior Demonstrator (SD) or Teaching Assistant (TA) during the practical.

There is a **compulsory** introductory meeting on normally the Monday of the first week of each term where groups are arranged and details of the timetable explained.

3. Staff involved with teaching laboratory

Each practical is led by a Senior Demonstrator (**SD**) who will provide an initial briefing about the practical. This briefing will cover the theory and practice of the experiment. They will discuss any specific safety issues associated with the experiment, the requirements associated with the laboratory notebook or longer report. They will also provide the assessment of your work (see Section 5). Following the briefing, the Senior Demonstrator will be present at times during the practical to answer questions, provide advice and may choose to assess your laboratory notebook towards the end of the practical or may assess it after the practical.

Also present throughout the practical will be Practical Class Technician (**PCT**) and a Teaching Assistant (**TA**). The PCT (Diana Passmore) has a lot of experience regarding the instruments in the laboratory and can provide advice. The TA will be an early-career researcher (usually a post-graduate research student) who will have experience of conducting laboratory research.

The overall academic lead for the teaching laboratories is the Practical Class Organiser (**PCO**), Sebastian Bonilla.

4. Conduct

One of the aims of the Materials Science degree is to teach you to be a professional scientist. The teaching laboratory is a professional space, and we expect an appropriate conduct in the laboratory. Here are some DOs and DON'Ts. It should be obvious why these are important in the laboratory, but talk to the PCT or PCO if you are not sure about any of them.

DOs	**DON'Ts**
DO pay attention to the PCT and demonstrators	DON'T eat, drink or put on make-up in the labs
DO read and follow safety instructions	DON'T use your mobile phone
DO concentrate on what you are doing to avoid mistakes	DON'T mouth-pipette or lick things
DO familiarise yourself with fire escape routes	- this includes sucking your pen!
DO keep fire doors closed and escape routes clear	
DO wear appropriate eye and hand protection	and a couple of "obvious" ones:
DO wash hands after working with chemicals	DON'T mess around
DO work in a fume cupboard with etchants and solvents	- if you do, you'll be required to leave
DO use minimum quantities of flammable liquids	DON'T wear inappropriate clothing and shoes
DO keep the labs clean	- e.g. sandals, short skirts, long scarves
DO speak in English at all times in the labs	- you'll be asked to modify your dress or leave
DO keep long hair tied back at all times	

Note: it is important that the only language spoken in the Teaching Labs is English - whether that be student-to-student or demonstrator-to-student - such that if incorrect (and potentially unsafe) instructions are given, there is a better chance someone overhearing them will realise and be able to act.

5. Assessment through laboratory notebooks and full reports

As a professional research scientist, it is necessary for you to learn to keep an accurate laboratory notebook as you are performing an experiment and to subsequently be able to write a longer report or scientific paper. _Both the laboratory notebooks and the longer reports are marked as part of your examinable coursework_. Your laboratory notebook will be marked for **every** practical (except 1P1 and 1P2 at the start of Michaelmas Term for Prelims).

You are required to write long reports for **three** of the practicals in an academic year. For Prelims, the first long report assessment is formative (the marks do not as examinable coursework) so that you will have received some feedback before writing the two that do count.

For each practical, your laboratory notebook will be awarded an integer mark out of 3. It is expected that most notebooks will receive a mark of 2 presuming they show an ability to accurately record the experiment. Notebooks that show some innovative thinking may receive a mark of 3. Unsatisfactory notebooks will receive a mark of 1. See Appendix A below for guidance on keeping a good laboratory notebook.

The longer reports will be written in the form of a scientific paper. These will be marked out of 13. Guidelines for writing a good paper can be found in Appendix B and C. A report must be typed or word-processed and converted to a pdf file prior to submission via the assignment tools on Canvas.

For both the laboratory notebooks and the longer reports you will receive feedback but not the mark because these are still subject to moderation by the examiners before being finalised. This is also a realistic example of the professional environment, where submission of a report will lead to feedback from independent assessor, but you don't receive a mark.

For Prelims, the 8 laboratory book assessments and 2 long reports add up to a total of 50 marks out of a total of 500 marks for the total of coursework and examination papers for the year. Thus each laboratory mark counts 0.2% to your final mark.

For Part I, 7 practicals have the laboratory notebook marked, and 3 practical require submission of the paper-style report, leading to a total of 60 marks out of 800 total for coursework and examination papers for the year, so each practical mark is worth 0.125% of your Part I mark and 0.083% of your overall degree mark.

For the exact guidance to assessments, please see the *Examinations Regulations* for your year.

6. Requirement to pass the practicals part of the course and penalties for late submission

Because experimental capabilities are an important part of learning to be a Materials Scientist, all candidates are required to pass the practical class part of the course for both Prelims and Part I in order to progress on course. Details of the requirements can be found in the *Examination Regulations*.

All scientists have to work to deadlines and follow ethical principles, this is also expected in your laboratory work. Penalties deducting marks will be applied for late work. Plagiarism is also taken very seriously by the university. See the Course Handbook for more details.

7. And finally

Remember, the more you put in, the more you will get out of the practical classes. Hands-on experience can be a great way to learn. Also remember to ask if you have any questions.

Asking good questions is what drives science!

Appendix A

Keeping a good lab notebook

Recording research data is as important as the experiment itself. If your lab notebook is well maintained and contains an accurate record of the research protocols used and the results obtained, it will be the basis to reproduce the experiment in the future (if needed) and to write scientific papers and reports.

It will also be a valuable source of information to claim a discovery or an invention, to prove that you have adhered to standards of good practice (e.g. in case of an accident) and that you have acted with academic and ethical integrity.

What is a lab notebook?

It is a record of your activities in the lab: what you did, how you did it, why you did it and what you observed as a result.

This includes mistakes and difficulties, which will often teach you more as you try to overcome them. The procedures and method you use might be standard or documented elsewhere. In that case, you should refer to them and there is no need to copy them again the notebook. However, if you are modifying them, you should include enough details so that other researchers could check/repeat your experiments.

In some cases, lab notebooks will be a legal document to prove patents/inventions and defend your results and actions from accusations of fraud or bad practice. The lab book is also your scientific legacy in the lab. When keeping a lab notebook, the question to ask yourselves is: “have I recorded enough information that I could still write a report on this many years later?”

The lab notebook doesn’t have to look perfect. It should reflect, in a practical and efficient way, your experiences in the lab. A key scientific skill is to learn to keep notes in the lab book while you are performing the experiment. Do not be tempted to use a “draft” lab notebook, for example on loose paper, and then write up something more polished at the end of the practical. This is not realistic of a working lab environment and it won’t bring you any extra marks. If the lab notebook is legible and shows the right content, it’s served its purpose.

There are different types of lab notebooks: bound/stitched, loose leaf/ring binder or electronic. They all have advantages and disadvantages:

- The bound notebook won’t allow you to change the order of your annotations or add extra data to an old experiment. However, it will keep its pages more reliably and it’s legally stronger. This is the format you’ll be normally using in the lab.
- The loose leaf notebook can be organized and sorted more flexibly, with all related data together, in the order you choose, but it can lose pages easily and it is harder to authenticate.
- The electronic notebook makes searches easier, can be read/edited in multiple devices and it is easy to share. However, the required electronic security might be hard to implement/guarantee, files can corrupt and data format might present compatibility issues in the future.

The bound lab notebook you have been given belongs to the Department and must be handed back to the Lab technician at the end of each practical.

For the practicals that require writing a report, you can photocopy any relevant pages before the practical finishes (time it accordingly to avoid photocopier “overbooking”). You are not allowed to remove pages from it, just void them if not needed.

Why do you need a lab notebook?

All scientific and professional research environments will require a detailed and consistent lab notebook.

When experiments take several days/months/years to complete, they might involve more than one researcher. It is therefore important that all critical details are recorded with enough level of detail for a different person to interpret or reproduce your results.

Your Prelims Practical Course might offer you your first opportunity to use a lab notebook efficiently, hence we will try to ensure that you develop good practice.

Using a lab notebook

A pen ('permanent' ink, ideally black) should be used to write on the notebook, since pencil can be erased (and generate authenticity issues). Your writing should be legible and clear.

The notebook should contain:

- A reference name so that it can be distinguished from other notebooks you use (E.g. Teaching Labs Practicals).
- In the cover page: Your name, year and email address.
- Numbered pages.
- Date/time for each experimental session.
- All the experimental entries from your practicals.
- Clear headings and subheadings for all relevant sections, including the title of the practical. Ideally, new practicals should start in a new empty page.
- A table of contents, with enough space to be expanded as needed (particularly when you use a bound notebook), and including all the experiments you describe in your lab notebook and where to find them (with a page number for cross-referencing).
    - You should leave several pages blank at the beginning or the end of the notebook for this purpose.

What should be recorded in a lab notebook?

A lab notebook should not contain long paragraphs of text. It is not a report and you won't have time to write extended text while doing experiments. Keeping your notes to a minimum is a key skill.

At the beginning of the session, write the name of the experiment, the date and the time. If the pages are not numbered, number them. No pages should come out of the notebook and you shouldn't skip pages. Write an appropriate heading for each of your entries

It is good practice to very briefly note the key scientific questions that the experiments are seeking to answer at the start of the notes for a particular practical. That can help keep the experiments focused on the main goals.

The experiments that form a practical should then be described in chronological order, whether they worked or not (good lab ethics). Entries should be sufficiently detailed, clear and legible for someone else to reproduce your procedure using your notebook and any materials you refer to such as the briefing document for that practical. There is no need to reproduce details that are in the briefing document, but you should note all your activities, stating if you are following a written procedure. If you need to change the procedure/protocol or decide between alternative ones, write down your reasons. If you make a mistake, cross it out with a neat line such that it remains legible and write the corrected information next to it. Don't erase or use white correction fluids (e.g. Tipp-Ex). If you need to add extra material (e.g. plots, photocopies, printouts), don't leave them loose inside the notebook, always staple or glue them to the pages.

If you are making manual measurements, for example from a gauge, then these should be recorded neatly in a table in your lab book. Some experiments are automated and the data is recorded directly into a computer. In this case, the filenames and locations of the data should be recorded in your lab book.

You may be expected to perform some initial processing of your data to get a numerical result. You may be using a software package such as Excel/Matlab/Python which is being used to convert, for example, forces to stresses. There is no need to show every step of the processing in your lab book – summarise what was done in a few sentences. You need to demonstrate the experiment is working (eg by getting an expected straight-line plot which you should include in your lab book) and to record any final numerical results.

For some experiments, it may be useful to perform some preliminary error analysis. Often one particular measurement is the dominant source of error, and you may choose to repeat that measurement more than others to try and reduce the error. Finally you might make some quick comments interpreting the results. Do they make sense? Do you think the experiment has delivered useful results

As much as the lab notebook needs to be up to certain standards, it is not more important than the experiment itself. Try to get the balance right between the time spent on both. Don't spend time on extra details or finishing touches that are only required on the final practical typed report

At the end of the practical, review your notes. Are you confident you could write a full report or scientific paper based on your notes? Is there anything else that needs to be noted down?

Appendix B

Writing a scientific report

Introduction

Writing reports that can be shared, evaluated, and reproduced is a very important part of scientific practice. In order to increase the impact of your findings and to ensure they reach as many peers as possible, publishing in a scientific journal is one of the most popular ways of sharing your research work.

Published papers have high standards of quality and should be clear, accurate and concise. It can be useful to think of a scientific report or paper as an opportunity for you to "teach" others about what you have learnt in your experiments. Your aim is to maximise the amount they "learn" so keep the report clear and easy to follow.

For your laboratory report, we expect a report in the format of a journal paper, using the journal *Acta Materialia* as the format to use. Look at some article in this journal to see how they are formatted.

Structure

When you organize your report as a scientific paper, it is important to order the sections right. Although there are no strict rules, there are some recommendations to follow. These are the main parts of a scientific paper:

1. Title: represents well the results and conclusions you are presenting.
2. Abstract: a brief summary of the report, stating the scientific question the work was trying to answer, include an outline of how your experiment was conducted and the methodology you used.
   a. Include, if relevant, some details about the samples used and methods for analysis, and the results or outcomes from the work.
   b. We are limiting the length of your abstract to a maximum of 300 words.
   c. (some people prefer to leave this for the end, once the whole article is ready)
3. Introduction: present the topic and its context, clarify the motivation for the work and explain the content of the next sections.
   a. briefly review some of the relevant background literature (describing what others have done before you), using citations to help the reader follow up.
   b. Introduce the important scientific concepts involved in the work at this stage so your reader is sufficiently informed to cope with the rest of the paper.
4. Methods: provide enough detail and information for others to reproduce your experiments.
   a. It should contain information about your samples (or software) and the methodology used, including what hardware/instruments and how.
5. Results and discussion: This section contains your results, described objectively. Incorporate your discussion to the results, with appropriate error analysis so that the results can be interpreted in a meaningful way.
   a. your interpretation of the results should explain to the reader what they mean.
   b. Some speculation is acceptable, although it should be clearly stated when not enough evidence exists to back them up.
6. Conclusions: This final section presents the outcome of the work by summarizing the findings in a more concise way, typically in the form of bullet points. The findings are often related to the motivation stated in the introduction section. Suggestions of potential future work can also be stated here.

Although **Appendices** are permitted in Acta Materialia manuscripts, we don't think they are necessary for your reports and are **not** allowed.

Working on your report

Once you have finished your experiments and have all your data ready and analysed, it is time to report your results. Even with a tentative structure, as explained in the previous section, writing the whole report might appear as a daunting task. For this reason, it might be easier to start from the sections that just require an objective description and then work on the discussion and conclusions. We have imposed a **3000 word limit for your manuscript** (excluding references and captions). This will help you focus on what is essential and prevent lengthy introductions and discussions.

Elsevier [1] describes this approach, which is used by many scientists, and suggests the following order:

- Start by preparing the figures and tables you are going to include in your report. You'll have to decide how to present your data. While tables provide numerical values they are not that common in scientific papers, figures/plots are more useful for comparison between experiments.
    - Remember to add errors and error bars, describe the contents concisely in the caption and reference them in the text.
- Check that your labels or any text in the figures are legible and bear in mind **you shouldn't use more than 10 figures**.
- Write the Methods section. This section contains information about how you performed the experiment. It should be detailed enough to allow another researcher to reproduce it. You should describe the samples, chemicals and instrumentation used.
- Write the Results. Here you will objectively describe what results you obtained from your experiments. Try to present them in an order that facilitates the story you are telling and makes them easy to understand. Present an error analysis, if appropriate, to allow your results to be interpreted in a meaningful way.
- Write the Discussion. Here you will explain what your results mean. Although you are allowed to speculate, you should always try to support your ideas with data or references.
- Write the Conclusions. Summarize your findings and their relevance. You can also use this section to suggest future work.
- Write the Introduction. Here you should introduce the topic, explain why it is relevant, what has been learnt in the past, its limitations and what you are trying to achieve. Introduce the main concepts that will be used later in the paper. Most of your citations/references are in this section. Make sure this section is balanced and does not become the main body of your report. The Introduction can also explain the structure of the paper to help signpost the reader.
- Write the abstract. The abstract summarizes what you did, what the important findings are and will play an important role in determining how many potential readers will find your report interesting. You can give away key results here but without many experimental details. A very short snapshot of the conclusions can be added as a last sentence. **Do not use more than 400 words for the abstract**.
- Choose the title
- Write up references

Details of how to submit your long report can be found in the Course Handbook

Assessment of your report

Your long report will be marked out of a total of 13.

For Year 1 students your first report will be marked, but the mark for this first report is formative and does not count to your overall Prelims year mark. The subsequent two reports will count towards your overall Prelims year mark.

For Year 2 students, 3 long reports count towards your Part I mark.

You will receive feedback on your report but the mark is finalised by the Prelims Moderators or the Part I Examiners and not released prior to their moderation.

The allocation of marks is as follows:

- Title, abstract and Introduction – 2 marks
- Description of methods used including methods of data processing and analysis – 3 marks
- Presentation of results including the appropriateness of figures and data presented, and the use of errors where appropriate – 4 marks
- Discussion and interpretation of results – 3 marks
- Conclusions – 1 mark

Reference

[1] https://www.elsevier.com/connect/11-steps-to-structuring-a-science-paper-editors-will-take-seriously

Appendix C

Example of a demo practical and associated report

I have created a demo practical, including a simple script, experimentation with data acquisition, and subsequent write-up. This provides you with a guide of <u>what an excellent report looks like</u>.

Demo Practical - Newton's Second Law

1. Aims of the Laboratory

The aim of this experiment is to verify Newton's Second Law of Motion by investigating the relationship between the net external force applied to a system and the resulting acceleration.

Students will:

- Demonstrate that acceleration is directly proportional to applied force.
- Estimate the effective inertial mass of the cart–pulley–hanger system.
- Develop skills in experimental measurement, data analysis, and scientific reporting.

2. Experiments

a) Setup: A cart of known mass is placed on a level track. A light string passes over a low-friction pulley, connecting the cart to a hanging mass.

b) Motion of the cart is measured using two timing sensors positioned near the pulley, which provide a value of the velocity after time t_{final}.

c) Acceleration is calculated as $a = dv/dt$, with the initial speed being zero, and the final speed measured by the final two timing sensors.

d) Procedure:

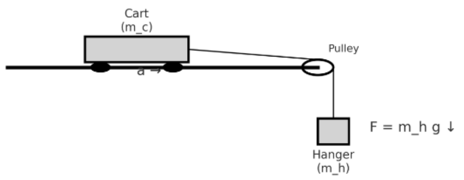
- Keep the total mass constant: cart + added mass + hanging.

- Vary the hanging mass in increments (e.g., 20 g, 40 g, … 100 g), which requires reducing the added mass.

- For each trial, release the system from rest and record acceleration.

- Repeat at least 10 trials per hanging mass for reliability.

Dynamics Cart with Hanging Mass (F = ma Experiment)



Safety Note: Ensure the pulley is secure and the string does not snag. Retrieve falling masses carefully.

3. Data to be Obtained

- Masses: cart mass (m_c), added cart mass (m_a), and each hanger mass (m_h).

- Force: net force $F = m_h g$ due to the hanging mass.

- Acceleration: average acceleration of the cart for each trial.

- Trial notes: environmental observations (friction, misalignment).

- All data should be logged in an excel file.

4. Questions to be Answered

a) Does the measured acceleration increase linearly with net applied force?

b) What is the slope of the a–F graph, and how does its inverse compare with the known total system mass?

c) Is there a significant intercept in the regression, and what does it suggest about frictional or systematic effects?

d) What sources of uncertainty most affect the results (mass measurement, timing, pulley friction)?

e) How might the design be improved to reduce systematic error?

5. Expected Outcome

Students should find that acceleration is proportional to force, with slope approximately equal to 1/M, where M is the effective mass of the cart plus attached masses. Small deviations from theory can be explained by experimental imperfections.

Student's Report (Example)

A Verification of Newton's Second Law Using a Dynamics Car

Abstract – Newton's Second Law of Motion, $F = ma$, is a cornerstone of classical mechanics, yet its precise experimental validation remains pedagogically important in engineering education. This study investigated the quantitative relationship between net applied force and measured acceleration in a cart–pulley–hanger system. A low-friction track supported a cart of 0.50 kg with an additional 0.10 kg hanging mass. Net force was varied systematically using hanging masses between 0.02 and 0.10 kg, yielding applied forces in the range 0.20–0.98 N (g=9.8 m.s^{-2}). Accelerations were obtained via motion analysis and logged into structured datasets. Linear regression of acceleration versus net force produced a slope of ($1/M_{eff}$) = 1.56±0.06 kg^{-1} and intercept b=0.03±0.02 m.s^{-2}, with R^2=0.995. The effective inertial mass estimated from the slope was M_{eff}=0.64±0.03 kg, in excellent agreement with the measured total mass of 0.62–0.70 kg. The negligible intercept indicated minimal frictional losses. These results confirm the linear proportionality between net force and acceleration and validate Newton's Second Law within experimental uncertainty. Sources of error included small uncertainties in mass measurement (±0.01 kg) and the timing resolution in the acceleration sensor. The experiment illustrates both the robustness of classical mechanics and the importance of systematic error analysis.

1. Introduction

Newton's Second Law of Motion, articulated in *Philosophiæ Naturalis Principia Mathematica* (1687), is one of the central pillars of classical mechanics. The law establishes that the acceleration a of a body is directly proportional to the net external force F acting upon it and inversely proportional to its inertial mass mmm, expressed compactly as $F = ma$. This deceptively simple relation underpins much of modern science and engineering, from the analysis of materials under load to the design of advanced mechanical and aerospace systems. Yet, translating the abstract law into precise experimental confirmation requires careful control of systematic effects such as rolling friction, pulley inertia, and air resistance, all of which can obscure the proportionality between force and acceleration.

Numerous instructional experiments have sought to demonstrate Newton's law in laboratory settings, employing apparatus such as air tracks, photogates, motion sensors, and video analysis (Thornton & Sokoloff, *Am. J. Phys.* 1990; Laws, *Phys. Teach.* 1997). These studies consistently confirm the linear relationship but also highlight the pedagogical value of quantifying deviations from ideal behaviour. The present work is motivated by two objectives: first, to give engineers direct engagement with experimental verification of Newtonian dynamics; and second, to evaluate quantitatively the agreement between the effective inertial mass inferred from acceleration–force measurements and the actual system mass. To achieve this, we employ a cart–pulley–hanger system, analyse the resulting motion with digital tools, and critically examine both the agreement with theory and the role of experimental uncertainties.

2. Methods

<u>Apparatus</u>

The experimental setup consisted of a dynamics cart (m_c=0.50 kg) running on a horizontal, low-friction aluminium track of length 1.0 m. Additional masses (m_a=0.02–0.10 kg) could be securely attached to the cart to vary the system's inertia. The cart was connected by a light, inextensible string (mass < 0.1 g, negligible relative to other components) to a mass hanger suspended over the edge of the track. The string passed over a low-friction plastic pulley of radius 2 cm mounted at the end of the track. Hanger masses were varied in increments of 0.02 kg between 0.02 and 0.10 kg, yielding applied forces in the range 0.20–0.98 N.

Acceleration was measured using a pair of infrared timing gates positioned 0.50 m apart along the track. The gates recorded the time taken for a flag attached to the cart to pass, allowing calculation of instantaneous velocity. Alternatively, a high-speed video camera (240 fps) was used for validation. All masses were measured with a calibrated electronic balance (±0.01 g).

<u>Procedure</u>

The cart–pulley–hanger system was assembled as shown schematically in Figure 1a. For each trial, the total mass of the cart plus any added weights was held constant while the hanger mass m_h was systematically increased in 0.02 kg increments. The system was initially held at rest with the string taut and then released smoothly to minimise additional impulses. The cart travelled freely along the track while the hanger descended under gravity. For each condition, a minimum of three runs was performed to reduce statistical variation, and outlier trials (due to string slip or pulley jamming) were discarded.

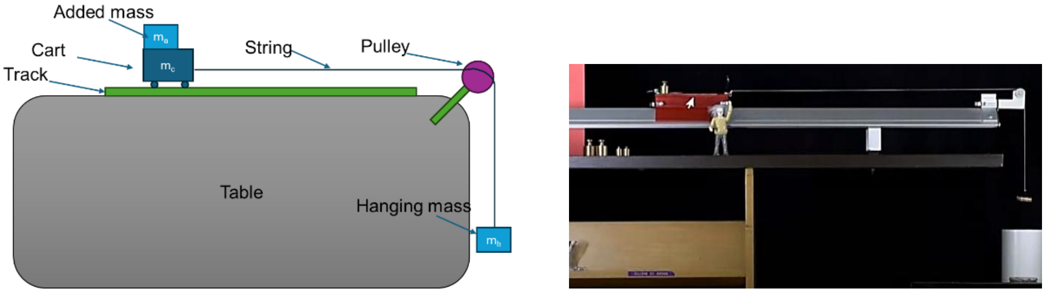


Figure 2. (a) Schematic diagram of experiment. (b) Photograph of experimentation.

Data Acquisition, Processing and Analysis

Raw timing data were exported to Microsoft Excel, organised by trial, and saved in CSV format. The net applied force was computed as

$$F = m_h g$$

with g=9.80 m s^{-2}.

Acceleration was determined from the slope of velocity–time data obtained from the timing gates, or from quadratic fits to position–time data in video analysis. Linear regression of measured acceleration + versus applied force F was performed using Python (NumPy, Matplotlib). The regression slope yielded $1/M_{eff}$, where M_{eff} is the effective inertial mass of the system, and the intercept provided an estimate of residual frictional acceleration.

Errors and Uncertainties

Statistical uncertainties were first quantified from the residuals of the linear regression, which capture the scatter of measured accelerations about the best-fit line. Systematic and random errors in the input quantities were then propagated explicitly. For the mass measurements, the electronic balance resolution (±0.01 g) was treated as a random uncertainty and propagated into both the total system mass and the computed net force $F=m_h g$. For the velocity and acceleration determinations, timing uncertainties arose from the gate resolution (±1 m/s) and from frame discretisation in the video analysis (1/240 s). These timing errors were converted into uncertainties in velocity by error propagation through Δv=Δx/Δt, and subsequently into acceleration by propagation through the linear fit of v(t)). The combination of mass and timing uncertainties was performed using standard Gaussian error propagation, ensuring that the reported effective mass M_{eff} and regression parameters were accompanied by robust confidence intervals that reflect both measurement precision and fit quality.

3. Results and Discussion

Force and Acceleration Data

Representative Net Force and Acceleration results are shown in Table 1, where averages from all 10 trials were obtained and listed. All data was recorded as an excel spreadsheet, and processed and analysed in Python. Figure 2 illustrates the obtained acceleration and Force data, including the statistical variations, and fitted curve.

Table 1. Net force and measured acceleration

m_h (kg)	F (N)	a (m/s²)
0.02	0.196	0.24 ± 0.05
0.04	0.392	0.54 ± 0.05
0.06	0.589	0.82 ± 0.05
0.08	0.785	1.11 ± 0.05
0.10	0.981	1.52 ± 0.05

Linear fit yielded slope 1.56±0.06, intercept 0.03±0.02, R^2=0.995.

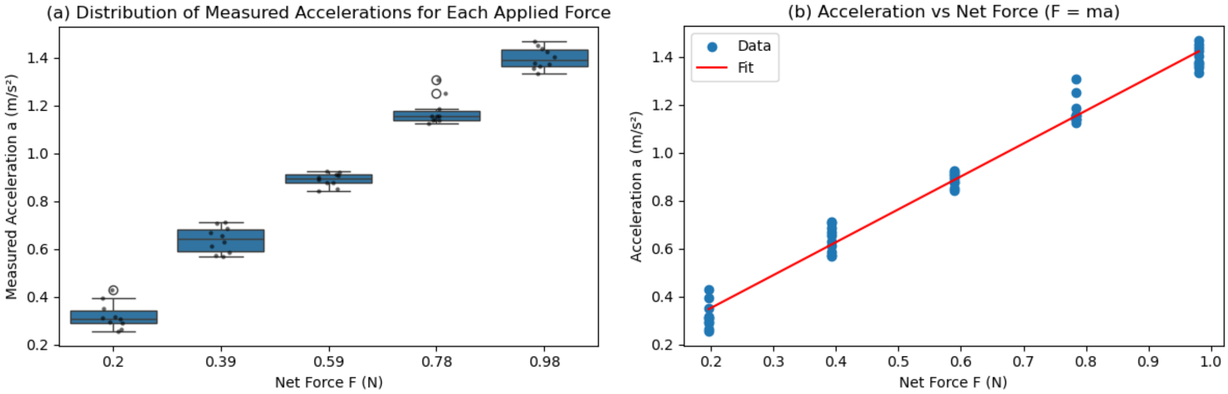


Figure 2. (a) Complete distribution of measured accelerations and masses for each combination of weights on the cart system. (b) Data fitting of the Acceleration versus Net Force for the obtained data.

Analysis and Interpretation

a) Requirement of same mass: The dynamics of a cart–pulley–hanger system can be described by Newton's second law applied separately to each body. For the cart+added mass m_c+m_a, the tension is T=(m_c+m_a)a. For the hanging mass m_h, the vertical equation of motion is m_hg−T=m_ha. Eliminating the tension gives:

$$m_h g = (m_c + m_a + m_h)a$$

so that the system acceleration is

$$a = \frac{m_h g}{m_c + m_a + m_h}$$

This denominator represents the effective inertial mass $M_{eff}=m_c + m_a + m_h$. If M_{eff} is held constant across trials, then acceleration is directly proportional to the net applied force F=m_hg, giving a linear relation of the form

$$a = \frac{1}{M_{eff}} F$$

Maintaining a constant effective mass is essential to obtain a linear a–F graph from which M_{eff} can be reliably determined.

*b) Linearity***:** The data demonstrated a clear linear relationship between net applied force and measured acceleration, in excellent agreement with Newton's Second Law of Motion, $F = ma$. This proportionality is the cornerstone of Newtonian mechanics: if the effective mass of the system remains constant, then doubling the applied force should result in a doubling of the acceleration. The near-perfect straight-line behaviour observed here provides a tangible confirmation of this theoretical prediction. For students, this reinforces the idea that fundamental physical laws can be directly verified through experiment, provided that sources of error are carefully managed.

c) Effective mass: From the slope of the acceleration–force graph, the effective inertial mass was calculated as Meff=0.64±0.03 kg. This value is fully consistent with the directly measured system mass of 0.62–0.70 kg (cart plus added weights and hanger). The close agreement illustrates not only the reliability of the method but also the power of regression analysis to extract meaningful physical parameters from noisy experimental data. This provides an opportunity to see how experimental uncertainty can be quantified and how results can be compared with theoretical expectations.

d) Intercept: The fitted regression yielded an intercept close to zero, indicating that the system exhibited negligible unbalanced forces when no additional hanging mass was applied. In theoretical terms, this suggests that rolling resistance of the cart and friction in the pulley were sufficiently small that they did not significantly bias the results. In practice, this finding underscores the importance of well-designed apparatus and highlights to students that non-ideal factors—often dismissed as "small"—can nonetheless be checked and quantified rigorously.

e) Uncertainties: The most significant uncertainties arose from the resolution of the timing apparatus (±1 ms for gates or 1/240 s for video frames) and from the precision of the mass balance (±0.01 kg). These propagated through to the calculated velocities and accelerations, introducing scatter in the dataset.

Additionally, rotational inertia of the pulley and minor misalignments of the track could have contributed systematic deviations, though their effect remained within the reported error bounds. Engaging students with these sources of error helps them to see experimental science not as an exercise in perfect confirmation but as a process of identifying, quantifying, and reasoning about limitations.

f) Design improvements: The experiment could be enhanced through the use of more precise force sensors to directly measure tension, or by employing an air track to virtually eliminate rolling friction. Digital motion sensors with higher temporal resolution would also improve accuracy in acceleration measurement. These refinements would not only reduce systematic error but would also provide students with a richer appreciation of how apparatus design influences the quality of scientific evidence. More broadly, recognising potential improvements encourages students to adopt a critical, research-oriented mindset, seeing laboratory work not just as verification of known laws but as an opportunity to practice the habits of real experimental physicists and engineers.

4. Conclusions and recommendations

This study has provided a clear experimental validation of Newton’s Second Law of Motion using a cart–pulley–hanger system. The measured accelerations increased linearly with applied net force, confirming the proportional relationship predicted by theory. The effective inertial mass, determined from the slope of the acceleration–force graph, was 0.64±0.03 kg, which is in excellent agreement with the directly measured system mass (0.62–0.70 kg). The regression intercept was close to zero, indicating that unbalanced forces such as rolling resistance and pulley friction were negligible within experimental error.

Uncertainty analysis showed that the dominant contributions arose from sensor resolution and timing accuracy, while systematic factors such as pulley inertia and small misalignments had a secondary role. Although these uncertainties were small, their identification and quantification illustrate the importance of careful experimental design and critical data analysis. Beyond simply confirming a law of mechanics, the experiment demonstrated how measurement precision, apparatus limitations, and statistical treatment all shape the credibility of scientific conclusions. The work thus not only validates Newton’s Second Law in a controlled setting but also serves as a valuable exercise in experimental physics.

Future extensions could involve exploring non-linear regimes in which the assumptions of the ideal model break down, such as introducing significant pulley inertia, variable frictional forces, or air resistance. Using higher-resolution motion sensors or direct force transducers would provide richer datasets and enable more sophisticated statistical analyses.