Cambridge University Press
978-1-108-41846-1 — Experimental Methods for Science and Engineering Students:
An Introduction to the Analysis and Presentation of Data 2nd Edition
Les Kirkup
Excerpt
More Information

1 Introduction to Experimentation

1.1 Overview: The Importance of Experiments in Science and Engineering

Scientists and engineers devote valuable time and resources to experimental investigations. Why do experiments? In the first place, scientific and technical advances rely on the support that a critical experiment, or series of experiments, can offer. New and established theories are tested through experiment. Devising and carrying out an experiment that provides a thorough test of a theory or confirmation of a discovery may be challenging, but until such a test is undertaken, and the results are confirmed independently by others, the theory or the discovery is unlikely to gain wide acceptance. Additionally, carefully performed experiments may reveal new effects that require existing explanations to be modified or perhaps abandoned completely.

The outcomes of the vast majority of experiments are usually known to only a few people. However, some experiments are so groundbreaking and influential that they attract international attention. An example of this is the detection of gravity waves by a group of scientists in 2015.[1] The existence of gravity waves, produced for example by an exploding star or colliding black holes, is a prediction that emerged from Albert Einstein's general theory of relativity. It took dedicated teams of scientists and engineers many decades to conceive and build instruments sufficiently sensitive to detect those waves. Those instruments have the potential to open a new window on the universe, allowing previously hidden cosmic events to be detected. The detection and analysis of such events hold the promise of new insights into the working of the universe.

Experiments performed as part of a college or university laboratory programme or project are unlikely to attract widespread attention. Nevertheless, they provide opportunities to acquire knowledge, skills and understanding through investigating the 'real world'. Such experiments have distinct advantages over the idealised descriptions and explanations of phenomena presented in textbooks: seeing

[1] See Castelvecchi and Witze (2016).

something happen has more impact than reading about it. *Making* something happen, as we do when we devise and perform an experiment, is even more memorable.

Experiments are not without their difficulties; some experimental techniques take time to master and occasionally we are confronted with data that require careful examination before we are able to draw out important features. In these circumstances a little patience and persistence go a long way.

In the process of carrying out an experiment, you may need to acquire proficiency in the operation of instruments of varying degrees of sophistication. It is not the purpose of this book to give instruction on the operation of instruments, but to offer advice of a more general and, I hope, enduring nature. Specific examples and exercises are included within the forthcoming chapters where these should assist in illustrating a data analysis technique or reinforcing an important point.

An experiment may be required to assist in addressing several questions, some of a general nature and others more specific. As examples:

- How does the energy efficiency of an organic solar cell depend on its temperature?
- At what temperature does a new ceramic material exhibit superconductivity?
- How does the flow of blood through a vein depend on the diameter of that vein?
- Has the speed of light changed since the universe was formed?

It is these types of questions that form the starting point for scientific investigations.

It is instructive to outline the stages through which a typical experiment develops. Though the stages are presented here in a particular order, in practice there can be much moving back and forth between stages as new ideas emerge, underlying principles are more thoroughly understood, more sensitive equipment becomes available and experimental skills are practised and improved.

1.2 Stages of a Typical Experiment

The Aim

This is the starting point of an experiment. What do we want to find out? The clearer and better defined the aim of the experiment, the easier it is to do the planning to achieve that aim. The aim may contain an idea or hypothesis that we want to advance or test. However, it is not unusual to begin with a specific objective in mind and while doing the experiment discover something interesting or unexpected. This is part of the excitement of experimentation. If the outcomes of all experiments were wholly predictable there would be little point in undertaking them. However, we must be aware of the risk of becoming side-tracked and failing to complete the original work.

The Plan

Once the aim has been decided, a plan is devised for achieving the aim. Decisions are made as to what equipment is required, which quantities need to be measured and how they are to be measured.

Preparation

The preparation stage involves organising the experiment. Equipment is collected and assembled. Safety issues are identified, and risks assessed and controlled for.[2] This might consist of, for example, wearing the appropriate personal protection equipment when dispensing a cryogenic liquid, or wearing safety glasses when operating a laser. If the experimental technique or instrument to be used is unfamiliar, instruction should be taken from an experienced user. This avoids wasting time and making avoidable blunders, as well as reducing the risk of damaging the equipment (and possibly yourself!).

Preliminary Experiment

Once the equipment has been assembled, a preliminary experiment is often performed. This promotes familiarity with the operation of the equipment, indicates which features work well and which need further refinement and gives a feel for what values to expect when the experiment is performed more carefully. The insight that a preliminary experiment offers can sometimes lead to reconsideration of the experimental method being used. It is fair to say that experienced scientists and engineers habitually, and sometimes obsessively, seek ways to improve their experiments.

Collecting Data

The data collection phase begins. Alertness and attention to detail at this stage tend to reward the experimenter with a valuable set of data. There is little more frustrating than spending an afternoon collecting data only to discover that some omission, such as neglecting to record the units in which the measurements were made, has rendered the data unusable.

Repeatability

The experiment is carefully repeated to verify whether the first set of data is representative and can be reproduced one or more times. The repeated experiment cannot be expected to generate *exactly* the same data. However, gross variations between sets of data is a warning that further investigation is warranted.

---

[2] Colleges and universities often devise their own laboratory safety guideline documents. An example of general laboratory safety guidelines can be found at https://www.osha.gov/Publications/laboratory/OSHA3404laboratory-safety-guidance.pdf

Analysis of Data

When data collection is complete, a most important question is asked: 'what do the data tell me?' If an experiment was performed with some hypothesis in mind, then this will indicate what data analysis method(s) should be adopted. For example, in an experiment to study the change in light intensity as the distance from the light source increases, a prevailing theory may lead us to believe that there is a power law relationship between intensity, I, and distance, d, where d is the distance between the light source and the detector. The power law relationship may be written

$$I = Ad^n, \tag{1.1}$$

where A and n are constants. The experiment would consist of measuring the light intensity as the distance between the light source and detector is varied. From the analysis of the data we would like to know how well equation 1.1 describes the relationship between I and d.

What Do the Data Tell You?

Once the data have been gathered and analysed, it is time to ask whether they are consistent with the initial hypothesis or whether the evidence is inconclusive or even contradictory. For example, in the light experiment described above, do the data provide us with enough evidence to be able to conclude that equation 1.1 *is* a good description of the relationship between intensity and distance?

Reporting the Experiment

When the experiment is complete, it is time to communicate what was done and what was found, in a clear and concise way. A report may be prepared describing the important features of the experiment such as the aim, method, data gathered, analysis method, discussion and conclusion.[3]

1.3 Documenting Your Work

An experiment may take as little time as an hour or extend over a considerable period of time. During this time, procedures may be devised and revised, apparatus assembled, data gathered and other steps taken, large and small, before the experiment is complete. Irrespective of the duration or complexity of the experiment, one thing is certain: the better the record of what has been done, the easier the task of presenting the work, perhaps in the form of a report to a laboratory supervisor. A convenient way of documenting work is to use a laboratory notebook.

[3] Report writing is discussed in Chapter 7.

1.3.1 The Laboratory Notebook

A laboratory notebook, also sometimes referred to as a logbook, contains a permanent record of experiments performed. For many scientists and engineers the notebook is an indispensable element of experimental work. In it they record details of an experiment, whether or not those details seem important at the time. Often it is not until sometime later that it emerges which are the important entries and which are of less value.

Notebooks are available in various sizes, but those with alternate pages of lined paper followed by graph paper are convenient to use in situations in which graphs need to be plotted. An alternative is to use a standard lined notebook and fix in graph paper as necessary. A hardback notebook, though more expensive than the softback variety, is a good investment as it tends to be more durable. In addition, there is generally less tendency for people to tear out pages from a hardback notebook. Such an act is frowned upon in all circumstances.

Though it may be tempting to write notebook entries in pencil so that they can be erased in the event of a mistake, a better option is to write consistently in ink. If a mistake has been made, a simple strike-through line can indicate an entry that should be ignored. This allows the entry to be read if it turns out sometime later not to be a mistake after all.

Many laboratory notebooks are not models of neatness (mine included) but they should represent a faithful record of what you planned, did and thought about while carrying out the experiment.

An electronic notebook is an alternative to a paper-based notebook. Electronic laboratory notebooks are increasing in popularity and have several attractive features. These include easily making backup copies of the notebook, the option of sharing the notebook with other people through the Internet and facilities for quickly searching through its contents.

Whether you use a paper or electronic laboratory notebook, it needs to be intelligible to at least one person – you! However, there may be situations in which the contents of the notebook form part of an assessment of an experiment or project you have carried out. In this case you need to remember that the notebook is going to be examined by someone else, so a logical layout of the account of the experiment is recommended. The order and description of elements that make up a typical account of an experiment are given in Table 1.1.

It is useful to number the pages of the notebook and to include a contents page. Page numbers are helpful when you want to refer to another piece of work in the notebook, and are especially worthwhile when describing a series of experiments covering several pages. For example, you might want to say *'the circuit used is that shown on page 27'*.

As described in Table 1.1, the notebook is performing two functions. The first is to document relevant information concerning the experiment, and the second is to

Table 1.1 Description of notebook contents

Notebook entries	Description
Date	Including this is good housekeeping and allows you to chronologically connect the contents of your notebook to other parts of your work. For example, it might be important to associate entries in your notebook with data that you gathered and stored on a computer on the same day.
Title	Leave the reader in no doubt as to what the experiment is about.
Aim of the experiment	Though this is something that may have already been decided on your behalf, it is so important that it bears repetition and should be given a prominent place in your notebook after the title of the experiment.
Description of instruments and apparatus	For many experiments, a brief list of apparatus used is sufficient. Recording details, such as the accuracy of an instrument, as provided in a manufacturer's calibration certificate, is good practice.
Sketch of apparatus	A fully labelled diagram of the experimental arrangement is worth a page of explanation and can assist in recalling the experiment long after it has been completed. A simple line diagram drawn freehand is all that is required.
Experimental method	If the method is given in the form of a set of instructions to follow, then the instructions can be 'cut and pasted' into the notebook. It is possible that you will have to depart from prepared instructions in some way or need to add to them, perhaps for the purpose of clarification. Such clarifications or additions need to be documented in your notebook. If you devise the method yourself then include enough detail so that you, or someone else, could repeat the experiment.
Data	It is usual to present data in tables, taking care to give each column in the table a heading which includes the unit of the quantity measured. There will be some uncertainty in every measurement you make.[a] An estimate of the uncertainty can be conveniently located in the heading of the table. Measured values are recorded *directly* into the notebook as they are made. The temptation to jot the values on scraps of paper should be resisted, as these are easily lost. Record the 'raw' data you collect. For example, do not convert units 'in your head', such as voltage values from millivolts to volts before recording them.
Comments/ Reflections	Thoughts or ideas may occur to you as your experiment proceeds, for example on how the experiment might be redesigned to improve the quality of the data. Such thoughts, as recorded in your notebook, can act as a source of inspiration when you perform another experiment. Importantly, comments recorded in your notebook may stimulate insights which can be included in a report of the experiment.
Graphs	Graphs are superior to tables for giving you 'the big picture' of the data and are often the first thing that someone examining your work will look at. Graphs must be presented properly with title, labelled axes and units.[b]
Calculations	If you need to make calculations based on your data, state the equation or relationship you are using. Work through the calculation as fully as possible in your notebook, making explicit the steps you have taken.

Table 1.1 (*cont.*)

Notebook entries	Description
Summary/ Conclusion	A laboratory notebook is not usually the place where you will present a detailed discussion of your work. However, at the end of the experiment it is standard to include a brief summary. For example, if the aim of the experiment was to find the efficiency of a silicon solar cell, you might report: *Based on the observations made in this experiment, the maximum energy efficiency of the amorphous silicon solar cell we studied was* $(3.1 \pm 0.3)\%$.

[a] We will consider uncertainty in measurement in Chapters 4 and 5.
[b] We will consider graphing in Chapter 3.

present it in a clear way so that it might be reviewed or assessed by others. While both functions are very important, as the length and complexity of experiments increase, these functions tend to become separated and the role of the notebook changes, with the emphasis remaining on making a faithful record of an experiment.

1.3.2 Example of Pages from a Notebook

If you are not familiar with laboratory notebooks, you might be curious as to what the contents of a typical notebook look like. In Figure 1.1 I offer two pages from one of my notebooks. The work relates to a study of the performance solar cells, the first stage of which was to make measurements on an amorphous silicon cell. The aim was to establish the output power and efficiency of the solar cell when illuminated by sunlight.

The pages shown in Figure 1.1 include details of the aim of the experiment, equipment used, the method and some data. It also contains a question requiring further investigation: has the increase in the temperature of the cells over the duration of the experiment affected the output power of the cells? It is quite common that, as an experiment is being performed, it inspires other questions that deserve attention.

Writing a report is so much easier when all the details you require are in one place – your laboratory notebook. It is unlikely that the notebook by itself will make complete sense to others, but it must make sense to *you* as it is from the notebook that a report which will be read by others can be prepared.

1.3.3 Documenting Open-Ended Experiments and Project Work

So long as experiments are short and reasonably self-contained, the approach to presenting the work in your notebook described in Section 1.3.1 works well. But what do you do if you are asked to devise an experiment requiring you to be responsible for the aim and method as well as gathering data, assessing uncertainties and so on? This

Cambridge University Press
978-1-108-41846-1 — Experimental Methods for Science and Engineering Students: An Introduction to the Analysis and Presentation of Data 2nd Edition
Les Kirkup
Excerpt
More Information

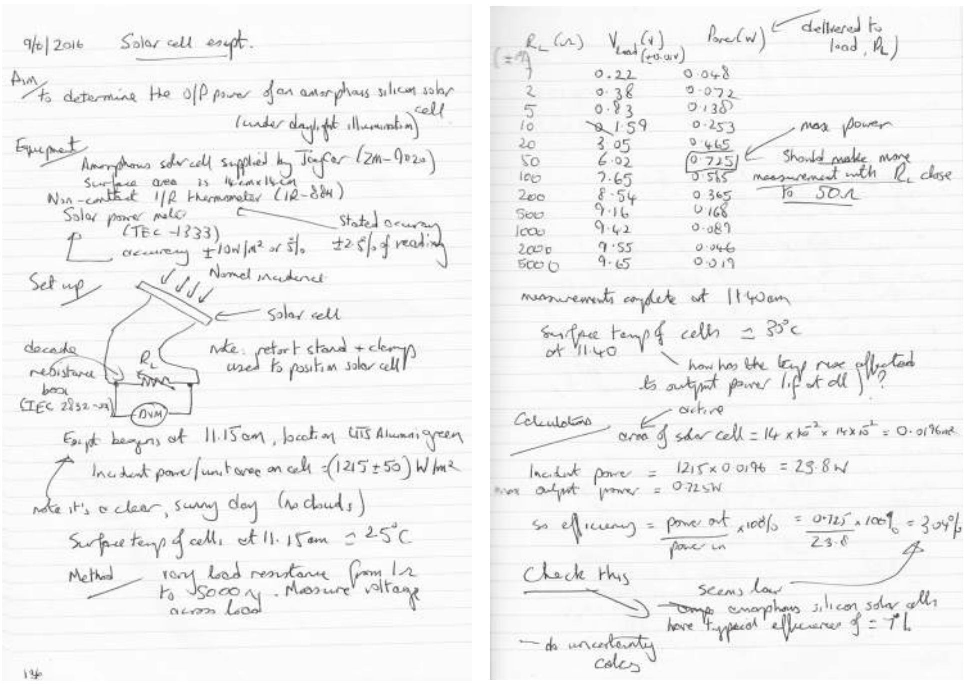

Figure 1.1 Example of pages from a laboratory notebook.

situation may well occur when doing open-ended experiments or when carrying out a project. Though the section headings appearing in the left column of Table 1.1 remain helpful, it is unlikely that you will be able to fill out the notebook in such a stepwise manner. Despite this, concisely and clearly documenting open-ended experiments and projects in a notebook is vital, as much of the information you will draw on when reporting the work to others will reside in your notebook.

1.4 Comment

In some circumstances a laboratory notebook can be unexpectedly valuable. If you are lucky enough to make a scientific discovery or technical advance, it is likely to appear first in your notebook. If, in addition, you are unlucky enough to be in competition with someone who claims to have made the discovery or advance first, you might find that your notebook becomes a vital piece of legal evidence to show what you did and when. For this reason, it is common for experimenters in industrial or government laboratories to have the contents of their notebooks verified regularly by a co-worker or supervisor. Beware, prosperity and reputation could be tied to your laboratory notebook, so use it well and keep it safe!

CAMBRIDGE

Cambridge University Press
978-1-108-41846-1 — Experimental Methods for Science and Engineering Students:
An Introduction to the Analysis and Presentation of Data 2nd Edition
Les Kirkup
Excerpt
More Information

2 Characteristics of Experimental Data

2.1 Overview: What are the Important Features of Experimental Data?

Measurements made during an experiment generate data which are recorded, analysed and reported. We need to display numerical data in ways which assist in analysis of those data. In addition, it is desirable to be able to examine the data as a whole so that trends can be recognised, for example the existence of a linear relationship between measured quantities. A table is an effective way of presenting data requiring manipulation, while a well-drawn graph is a revealing pictorial representation.

There are several questions to consider while gathering experimental data:

(i) What is the unit associated with each measurement?
(ii) How much variability is there in the data?
(iii) What should be included in a table of data?
(iv) Can we estimate or anticipate the size of a quantity before it is measured?

We now turn our attention to these and related questions.

2.2 Units of Measurement

At the heart of an experiment lies measurement and measurement requires a system of units. When a scientist or engineer claims to have made a breakthrough, perhaps developing an alloy with excellent corrosion resistance at high temperatures, other workers in that area of science or engineering want to know as many details of the characteristics of this material as possible. These might include its melting point, density, thermal conductivity, heat capacity and crystal structure.[1]

[1] A quantity, such as the melting point of an alloy, that we wish to determine through measurement is sometimes referred to as the *measurand*.

Cambridge University Press
978-1-108-41846-1 — Experimental Methods for Science and Engineering Students:
An Introduction to the Analysis and Presentation of Data 2nd Edition
Les Kirkup
Excerpt
More Information

Table 2.1 Fundamental SI units

Quantity	Name of unit	Symbol
Mass	kilogram	kg
Length	metre	m
Time	second	s
Electrical current	ampere	A
Temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

Above all, *quantitative* estimates of the properties are needed. These permit measurements made in other laboratories (perhaps on the same alloy in another part of the world) to be compared directly with the original work. A starting point for that comparison is that everyone agrees on a set of units of measurement and uses those units consistently when the results of experiments are reported.

2.2.1 The SI System of Units

Globally, the most widely used system of units in science and engineering is the Système Internationale or SI system, and it is the one we will use throughout this book.[2] At its core are seven fundamental units, as shown in Table 2.1. Other units are derived from the fundamental units. An example of a derived unit is the metre per second (written m/s or $\mathrm{m\,s^{-1}}$), which is a unit of velocity.[3]

The International System of Units by BIPM[4] is an excellent source of information on the fundamental units, how they are defined and how they may be combined to give a host of derived units. Many of the derived units have been given names which may be familiar to you. As examples, the newton, volt, watt and joule are all derived units in the SI system.

In pursuit of our goal of effective presentation and analysis of data, we should remember this: *Whenever we fill a table with data, plot a graph or make a remark concerning measurements or calculations based on those measurements, we must* ***always*** *state the units in which we are working.*

[2] We will not use SI units exclusively. Units such as the minute and the degree (which are not SI units) are so commonly used that examples will be given that use these units.

[3] Note that it is equally acceptable to write derived units using the slash mark, /, as in m/s, or using exponents, such as $\mathrm{m\ s^{-1}}$, and is generally a matter of preference which you use. I prefer using the slash mark except where it is clearer to use exponents.

[4] BIPM stands for Bureau International des Poids et Mesures. The BIPM document detailing the International System of Units can be found at http://www.bipm.org/en/publications/si-brochure/.