Experimental Physics for Students

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Preface

This text contains descriptions of about two hundred experiments suitable for an undergraduate course in Physics. Every experiment has been undertaken in the Physics laboratories at The Polytechnic of Central London, often with the valuable help of students and with the advice and assistance of members of the Physics staff.

For students in the United Kingdom, the standard of these experiments ranges from the second year of the Advanced Level G.C.E. course through to the first two years of study towards an Honours Degree in Physics, or all three years in a Science or Engineering Degree course in which the subject of Physics forms a significant part. It is regarded as of major importance that such courses should essentially involve the student in spending a considerable amount of time conducting individual experiments in the laboratory. Furthermore, it is considered that such experiments should cover a number of the fundamental aspects of Physics in illustration and extension of the accompanying lectures, should give the student first-hand experience of a variety of methods and instruments, should lead to an appreciation of the importance of errors and their treatment and, in the earlier parts of the laboratory course, should make use of simple apparatus to ensure a true understanding of principles not confused by assumptions about the operation and performance of complex measuring equipment.

The experiments included cover the main sub-divisions: optics, mechanics of solids and fluids, sonics, thermal phenomena, electrical measurements, magnetism, physics of the atom, radioactivity and nuclear physics, electronic devices and principles (but not modern electronic circuitry). Throughout there is considerable emphasis on simple statistical methods of treating errors. There is also more emphasis on technology than has been usual in such texts in the past: for example, a very considerable amount of scientific research is carried out at sub-atmospheric pressures, so experiments on the techniques involved are included.

Since the 'project' type of experiment – in which the student is exposed to a practical problem to be solved for which the results are unknown or not so specific as in the standard text-book – is regarded as important, several suggestions about such 'projects' are made in this text. In general, however, it is maintained that such 'projects' should mainly be left to the latter stages of the course on the basis that a good deal of formal experimentation is desirable to gain a proper appreciation of fundamental ideas, instruments and methods.

In addition to its use by the undergraduate student, it is expected that this book should prove to be a useful acquisition in the science library in the more junior college or school as a source of information to teachers and pupils who wish to develop methods and ideas in their classes outside the usual syllabuses.

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1 Errors of Observation

1.1 Discussion of the results of an experiment

As an example, consider the results of experiments to determine by the use of a Michelson interferometer the wavelength of almost monochromatic light (Section 2.5).

The determination of the wavelength of the orange-yellow line from a sodium discharge lamp (nominally 5893 Å) was repeated ten times by each of three students. The results are given in Table 1.1.

TABLE 1.1.

Determination of the wavelength λ of the orange-yellow light from a sodium discharge lamp.

Student (1) (Å)	Discrepancy from mean value	Student (2) (Å)	Discrepancy from mean value	Student (3) (Å)	Discrepancy, from mean value
6002	+100	6200	+233	5897	−3
5933	+31	6124	+157	5852	−48
5826	−76	5700	−267	5983	+83
5846	−56	6008	+41	5977	+77
5862	−40	6072	+105	5920	+20
5906	+4	5858	−109	5903	+3
5916	+14	6038	+71	5906	+6
5873	−29	5886	−81	5870	−30
5932	+30	5964	−3	5836	−64
5923	+21	5822	−145	5851	−49
Mean 5902		5967		5900	

* 1 Å (Ångstrom unit) = 10^{-10} m = 10^{-1} nm

All three students hoped that their observations would give a mean value of 5893 Å for the wavelength of the light. The overall mean of the determinations recorded in Table 1.1. is 5923 Å, which is an error of +0·51%. This is very good for most undergraduate experiments. But some interesting facts and queries have been revealed:

(*i*) The overall mean of 5923 Å is 30 Å greater than the true value. Is this error real and can it be said that the instrument is faulty?
(*ii*) Are the determinations made by the various students significantly different? Alternatively, as each student used a different part of the coarse scale, is the micrometer screw cut uniformly? In a sufficiently lengthy experiment, the performance of the students and the uniformity of the screw could be investigated.
(*iii*) One of the determinations by student (2) is 5700 Å, which is erroneous by −4·7% of the correct value. Is this a serious mistake due to faulty observation? Should this observation be disregarded? What is the essential minimum number of observations needed? The rights and wrongs of rejection of any (or all) of the observations need discussion.

To stress the considerations under (*iii*), another student obtained one value of 6475 Å in a series of ten observations, and consequently must decide whether it should be kept or rejected. It may demonstrate the unreliability of the apparatus or bias the mean value unjustifiably. The value of 6475 Å seems a gross mistake. Is rejection justified? If one observation is rejected, why not some of the others? Are all the observations wrong? The process could be continued until only one observation remains, but some standard for rejection is essential because different observers might have different ideas on which one is correct. Statistics and not personal prejudice will provide the necessary criterion for rejection and will give the probability of obtaining a wild observation.

In this Michelson interferometer experiment, we are fortunate in knowing the correct result. In most experimental work outside student laboratories, the correct result is not known. If it were, the experimental work would be unnecessary. A criterion for rejection of results consequently becomes a major requirement.

As a general rule in an 'open-ended' experiment, the experimentalist should follow the advice of an eminent biologist 'to treasure the exceptions', recognize their existence, and have a criterion for rejection. Further discussion of this topic is given in Sections 1.4 and 1.14.

1.2 Definitions of simple terms

(*i*) *The mean.* A number of results from an experiment are usually averaged to give the mean value. For example, $\overline{x}$ is the mean of a number n of determinations where the values recorded are $x_1, x_2, x_3 \ldots x_n$ and

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots x_n}{n}.$$

It is important to record also the variability of these observations. Thus the experimenter should be able to state that the value is the mean value (e.g. $\bar{x}$) plus or minus a parameter which denotes the variability of the observations due to random errors.

This variability is best expressed as the *standard deviation of the mean,* s_{m} which is defined in Section 1.3. The final result of the experiment would therefore be expressed as

$$\bar{x} \pm s_{\mathrm{m}}$$

where $\bar{x}$ is the mean value.

(ii) The error. The term *error* has two main meanings. It may be the difference between an experimental result and the true value, where this is known. For example, the precision work that has been done on the measurement of the speed of light gives a value of $2{\cdot}99793 \times 10^8\,\mathrm{m\,s^{-1}}$. In a comparatively simple student's experiment the mean result is $3{\cdot}05 \times 10^8\,\mathrm{m\,s^{-1}}$. The error is simply stated to be $(3{\cdot}05 - 2{\cdot}99793) \times 10^8 = 5{\cdot}207 \times 10^6\,\mathrm{m\,s^{-1}}$.

In many cases of experimental work, the true result is not known. The error, or standard error is then best expressed as $\pm s_{\mathrm{m}}$, where s_{m} is the standard deviation of the mean of n observations (see Section 1.3).

Random errors are minor experimental or accidental errors due to errors of judgement, or mildly fluctuating conditions which cannot be controlled. There are many causes of such fluctuations.

Systematic errors are constant errors which cause all results to be incorrect by roughly the same amount in the same direction. Care must be taken in the interpretation of systematic error.

(iii) Probability. A measured value may be less than, or greater than a certain figure.

In general, the deviations of individual observations from the mean value $\bar{x}$ may be plotted to give a *Gaussian distribution curve* (Section 1.12), also known as a normal distribution.

This Gaussian distribution will be obtained if the number n of observations is large. In many experiments time forbids that n is a large number. The plotted curve may then well depart from the Gaussian distribution. Provided the number of observations is adequate, however, the Gaussian distribution may be assumed and used as a standard of judgement. A feature of this distribution is that 68% of all observations lie between $\bar{x}$ and $\bar{x} \pm s$ and 95% of all observations lie between $\bar{x}$ and $\bar{x} \pm 2s$ where s is the standard deviation.

(*iv*) *Populations and samples.* A population is involved when the number of observations is very large, ideally infinity. In practice, *samples* are encountered in which the number of observations is finite. An important use of statistics is to test the significance of a sample value in comparison with the certainty of a population value.

1.3 The calculation of error

In the Michelson interferometer experiment (Sections 1.1 and 2.5) the mean error of 30 Å might be allowed for as being a systematic error, but this is not known, as yet. If this were done, the observations would still show some variability, which might be called the random error. Both types of error are of interest.

To assess the random error, there are two possibilities;

(*a*) The range w could be taken as the difference between the largest and the smallest value recorded. This is simple but useless because it uses only two observations, both of which might be gross mistakes.

(*b*) The preferred alternative is to utilize the *variance* s^2 of a sample, which is the sum of the squares of the differences between the observations and their mean divided by $(n-1)$, where n is the number of observations, i.e.

$$s^2 = \frac{\Sigma(x-\overline{x})^2}{n-1} \qquad (1.1)$$

s is known as the *standard deviation;* $\overline{x}$ is the sample mean.

The variance of the population is given by

$$\sigma^2 = \frac{\Sigma(x-\mu)^2}{N} \qquad (1.2)$$

where μ is the population mean, and $n = N$ is now a very large number; but in experimentation we are concerned exclusively with samples rather than populations because the number of observations is limited, so Equation (1.1) is the important expression.

The standard deviation has been called the standard error of an individual observation. *The standard deviation of a mean* of n observations may be shown to be s_m, where

$$s_m = s/\sqrt{n} \qquad (1.3)$$

Experimental results should be reported in such a way that the accuracy of the mean is known. If s and n are given, s_m can be calculated, and using a knowledge of the Gaussian or normal distribution, the probability of obtaining a certain error is known. The calculation of s may be simplified by using in place of Equation (1.1) the relationship

$$s^2 = [\Sigma(x)^2 - (\Sigma x^2)/n]/(n-1) \qquad (1.4)$$

The normal or Gaussian distribution concerns a population (i.e. a very large number) for which the mean and the variance are known, but all experimental data is based on small samples (i.e. n is small) and as the true variance is unknown, a slightly different error distribution has to be used: this is the t distribution (Section 1.13). t has its own probability distribution, any specified value of t being exceeded by a calculable probability, and tables are available to give t values for various conventional probability levels. This provides a method of testing whether a mean found from experimentally determined values differs significantly from any proposed value. In this case, the statistic t is defined from

$$t = (\text{measured value} - \text{true value})/s_m \qquad (1.5)$$

and this must exceed certain values listed in the statistic t table (Appendix A) to establish a significant difference. To illustrate the process, we will revert to the experiment.

1.4 A re-assessment of the results of the interferometer experiment (Section 1.1)

To illustrate the ideas of Section 1.3, consider again the results recorded in Table 1.1.

Student (1): mean value of λ determined by the experiment with the Michelson interferometer is 5902 Å.

The value of s^2 is calculated from either Equation (1.1) or (1.4). Using the former, the values of $(x - \bar{x})$ in this equation are those recorded in the second column of Table 1.1. Thus

$$s^2 = \frac{100^2 + 31^2 + 76^2 + 56^2 + 40^2 + 4^2 + 14^2 + 29^2 + 30^2 + 21^2}{(10-1)}$$

$$= \frac{23867}{9} = 2652$$

Therefore

$$s = 52\,\text{Å}$$

Also, from Equation (1.3)

$$s_m = \frac{52}{\sqrt{10}} = 17\,\text{Å}$$

By such calculations, the results of the three students are expressed as:

Student (1): mean λ = 5902 Å; s^2 = 2652; s = 52 Å; s_m = 17 Å
Student (2); mean λ = 5967 Å; s^2 = 23040; s = 152 Å; s_m = 48 Å
Student (3): mean λ = 5900 Å; s^2 = 2552; s = 51 Å; s_m = 17 Å

The overall mean of all 30 observations recorded by the three students is 5923 Å with $s_m = 18$ Å, so $\lambda = (5923 \pm 18)$ Å.

Certain conclusions can be made;

(*i*) The statistic t is given by Equation (1.5) to be

$$t = \frac{5923 - 5893}{18} = \frac{30}{18} = 1{\cdot}67$$

In Appendix A it is shown that t must exceed 2·045 for a difference to be significant when based on 30 observations (Section 1.13). The overall mean of 5923 Å is therefore not significantly different from the true value, known to be 5893 Å.

Again, for ten observations t must exceed 2·26; similar calculation shows that no student determined any significant difference between his mean and 5893 Å.

(*ii*) It follows that inspection reveals no significant difference between mean values obtained by the three students. However, a further application of the t test enables two means to be compared.

Thus

$$t = \frac{\overline{\lambda}_1 - \overline{\lambda}_2}{\sqrt{\left[\dfrac{(n_1 s_1^2 + n_2 s_2^2)(n_1 + n_2)}{(n_1 + n_2 - 2)(n_1 n_2)}\right]}}$$

where n_1 and n_2 are the numbers of observations in each group, i.e. ten in this case, whilst s_1^2 and s_2^2 are already given, i.e. 2652 and 23 040 for the first two cases.

(*iii*) Concerning the observations produced by each student, the distribution may be checked roughly for normality despite the small sample size.

Student (1): $s = 52$ Å. According to Section 1.2 (*iii*) we would expect 68% or seven of his observations to be in the range 5902 ± 52 Å. Actually eight are in this range and the other two are in the range 5902 ± 104 Å. No observation differs from the mean by more than $2s$.

Student (2): $s = 152$ Å; 68% or seven of his observations are expected in the range (5967 ± 152) Å. Actually seven are in this range and the other three are in the range (5967 ± 304) Å. No observation differs from the mean by more than $2s$.

Likewise in the case of student (3), no deviations exceed $2s$.

In all this work therefore none of the observations is unreliable. However, the controversial value of 6475 Å (Section 1.1) obtained in another group of observations with an s of 144 is more than $3s$ from the mean value. This value has a probability of about 2 in 1000 of occurring, and we might fix our standard of rejection of an observation as being in excess of $3s$. The value of 6475 Å is consequently rejected as a wild or gross mistake, and the mean and standard deviation is recalculated from the remaining nine observations. Of course border-line cases occur and one might choose a lower value than $3s$; this does not matter provided we state our standard.