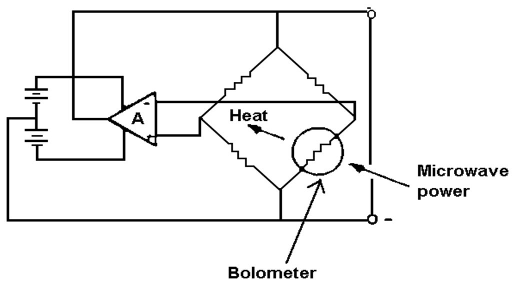

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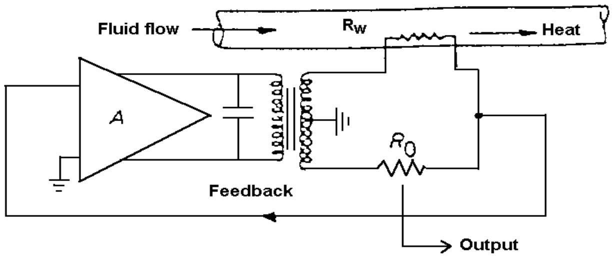

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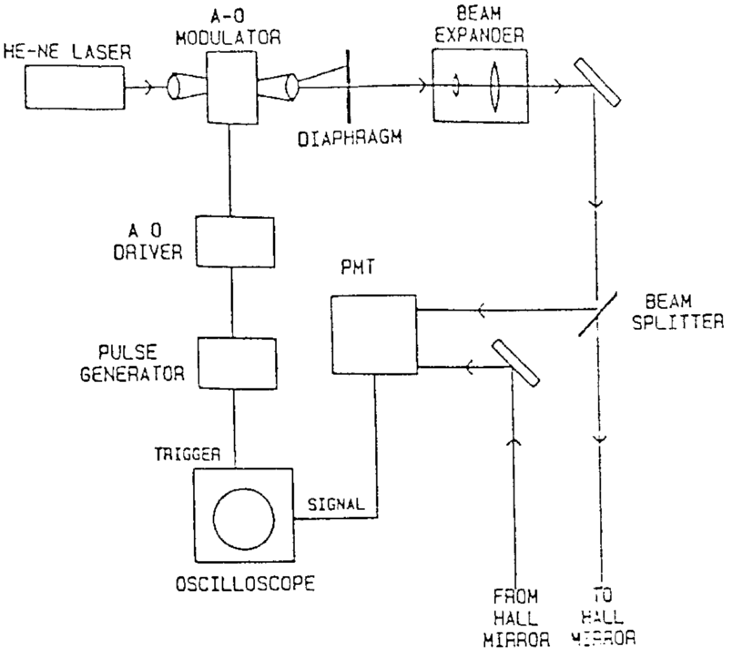
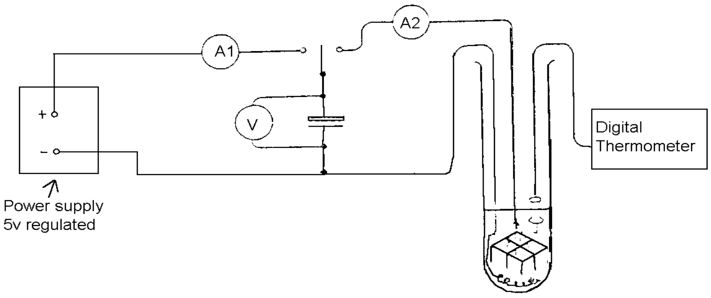
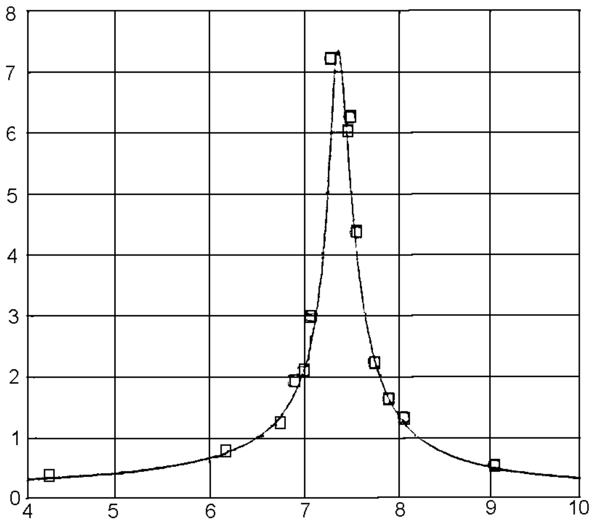
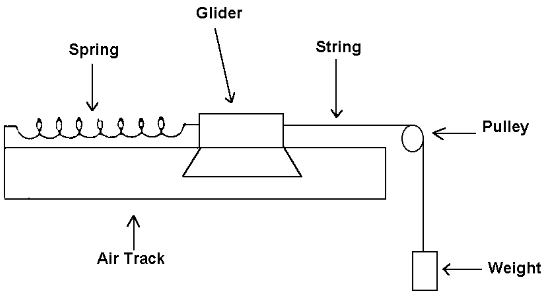


Laboratory Manual







School of Physics, University of Exeter
September 2009

Contents Page No.

CHAPTER 1

THE LABORATORY MODULES

1.1 Objectives and Assessment

The modules involving laboratory work for Honours Physics students extend over three or four years. The overall aim of laboratory work is to train each student to become a competent experimental physicist who is able to research a topic, to carry out an investigation satisfactorily, interpreting the results appropriately, and to interact effectively with managerial and technical support staff.

This manual relates to the first two years of laboratory work. The main emphasis of the modules is different in each year, as detailed below, though the distinction between the first two parts can be blurred in the case of able students who are well grounded in elementary practical work.

1.1.1 First Year Physics Laboratory

This module is designed to bring all students up to at least a minimum standard of competence in all the common aspects of laboratory work. The experiments usually complement topics met in the lecture courses, but are not intended to illustrate fully or to follow those courses. In addition to the Physics Laboratory module discussed in this booklet, most first-year students also do experiments in the Electronics Laboratory as part of a separate electronics module.

The aim of the course is to introduce students to the experimental practices in a laboratory and develop the basic skills essential for scientific work.

Full details of the first year physics laboratory module are to be found on:

http://newton.ex.ac.uk/teaching/resources/fyo/phy1110/

1.1.2 Second Year Physics Laboratory

This module builds on the preceding one. The experiments are more detailed, and sometimes more exotic, than before and may involve more advanced techniques. They are sometimes open-ended and usually take two or more six-hour sessions for completion. Most complement material lectured during the second and subsequent years but some, for which the theory is not covered directly in lectures, are included with the aim of extending a student's overall view of physics.

The course aims to develop a wide range of experimental skills, careful record keeping and the critical interpretation of data. During semester II students undertake an extended experiment, which allows them to implement and demonstrate some of the skills they have acquired. This will also be assessed by oral presentation.

Full details of the second year physics laboratory module are to be found on:

http://newton.ex.ac.uk/teaching/resources/au/phy2017/

Students enrolled on this module must read all the information on these web pages.

1.2 Technical Resources

1.2.1 Technician

The general maintenance of the equipment in the laboratories is the responsibility of the technician in charge of the laboratory. You should report any faulty equipment to him so that it can be repaired promptly.

1.2.2 Library

A small collection of textbooks relevant to practical work is kept in the IT suite within the laboratory. These can be used during the laboratory class. They are, however, reference books and must on no account be removed from the laboratory.

1.2.3 Computers

The computers in the Part I laboratory, located in the IT suite, are provided for use in data acquisition and analysis. A collection of programs is available which can be used by a novice to assist with data analysis in some of the experiments. Word-processing facilities also exist both here and in the 3rd floor Computing Laboratory. Several experiments within the lab have their own computers associated with them. The Laboratory is a WiFi hotspot enabling connection to the University network.

Whilst students will be encouraged to use these computers to help solve their physics problems, **the installation of games or any unlicensed software is strictly forbidden**.

Anyone who wishes to use the associated laser printing facility for private use should see the Part I laboratory technician. This will be charged at cost.

1.3 Safety in the Laboratory

Safety in the laboratory requires the strict observance of certain rules:

- Smoking is not permitted.
- Food and drink are not to be consumed in the laboratories.
- Coats, bags etc. must not be draped over equipment or placed on benches where experiments are set up. Please use the coat hooks provided.
- The workbench should be tidied up after use and equipment returned to the condition in which it was found.
- No one is permitted to work alone in the laboratories outside the normal hours.
- Any injury, however trivial, must be reported to a Demonstrator. This is in order to comply with the legal requirements of the Compensation Acts. First Aid kits are available.
- Breakage or faulty apparatus should be reported to a Technician or a Demonstrator. Repairs to apparatus should not be attempted without seeking proper advice.
- Radiation safety: there are University and School rules that must be obeyed at all times when working with ionising radiation. These are included in the manuscripts of all experiments involving the handling of radioactive material.

CHAPTER 2

APPROACH TO PRACTICAL WORK

At the heart of most practical work are the acquisition, recording and analysis of data. To get the best out of an experiment you need to be methodical, to understand what you are doing and to be alert to the unexpected. To a small extent in an extended experiment, to a greater extent in the third- and fourth-year projects and to a very great extent in research and professional work the ability to design experiments is also important. During this course, however, the emphasis will be on the proper use of apparatus that already exists, on maintaining a good laboratory notebook and on writing concise and critical accounts of what you have done.

We expect information to be **recorded directly** into the laboratory notebook during laboratory sessions. Loose scraps of paper will not be tolerated. The object is to record sufficient information so that at some later date you are able to see all you did, what measurements you took and what results you obtained. This may not appear to be particularly relevant to experiments of short duration but will be most important later when you have to produce a project report from bulging notebooks containing two terms' work. The notebook should contain **at least** the following:

- Title and aim of the experiment.
- Verbal description, block diagram, circuit diagram of apparatus (as appropriate) with records of the sensitivities of pieces of equipment where known, etc.
- All measurements neatly tabulated and described.
- Notes and comments on any special features of the experiment. In particular, record the bright ideas that you have.
- Calculation of the results, graphs and assessments of overall reliability.

The **completion** of an experiment consists in writing a further one or two sides in which the results are gathered together and interpreted. In particular errors should be indicated, possible improvements in the execution of the experiment suggested and answers given to any questions contained in the labsheet. To assist you in improving your performance there follows a checklist of items that contribute to the assessment of each experiment. The following sections of this chapter offer hints, guidelines and information about the topics in the checklist.

Planning:
  Evidence of planning the experiment (in the form of a preliminary report)
  Preliminary experiment(s)
  Identification of largest source of error

Execution:
  Taking and tabulating measurements
  Plotting graphs
  Treatment of systematic error
  Estimation of random errors

Analysis:
  Calculations
  Quality of results
  Comparison with theory
  Understanding questions raised

Conclusions:
  Concise summary of results
  Discussion

2.1 Planning

2.1.1 First task

Always start by reading the labsheet from beginning to end and make sure that you know what the experiment is about before starting to use the apparatus. In addition you are strongly advised to look up relevant background material in the Library. Many of the labsheets have references to books or articles that are readily available.

2.1.2 Instrumentation

Some instruments may be unfamiliar to you. We keep a collection of manufacturers' manuals and technical specifications, which may be consulted concerning correct usage and the precision to be expected. Always note down the models of standard instruments you use and the precision claimed for them.

Plan the layout of the various instruments and apparatus on the bench so that scales may be easily read and controls easily adjusted; electrical connections should be kept as short as possible and not tangled up.

2.1.3 Preliminary experiments

In nearly every investigation it is useful to make a trial run first. This serves several purposes:

- The experimenter gets a feel for what has to be done and how it may be done efficiently.
- The apparatus is checked for correct functioning.
- Suitable ranges of variation for the variables are determined.
- An estimate of errors can be made. This can influence how the full experiment is performed in that more attention can be given to the quantity, which gives rise to the largest error.

2.1.4 Identification of the largest source of error

The largest source of error is the Achilles heel of any experiment. You need to know what it is in order to make the most of your observations. It may be that a more precise instrument can be substituted; or you may find that changing your strategy of observation leads to greater precision.

2.1.5 Role of theory

If the theory of what you are investigating is available it may well give a good guide to the ranges of variables to be explored. It will also influence the way in which your measurements will be processed so that the comparison of experiment and theory can be most effectively made.

2.2 Execution

The main part of the experiment can now be carried out. This usually involves the making of specific measurements and cycles of activity in which apparatus is adjusted, readings are taken, the data are processed, points are plotted on graphs and so on. It is essential to be **methodical** and to record directly into your notebook (recording on loose sheets of paper is not acceptable). Make a point of recording what you are going to do, sketch the experimental layout, draw the circuit diagram etc. The goal is clarity rather than excessive neatness and your notebook should resemble a diary, not a jotter.

Awareness of error should be in your mind throughout the execution of an experiment. This is because error determines the reliability that can be placed on the results and conclusions of an experiment. Errors are not shameful mistakes to be hidden or minimised, nor should they be treated as a ghastly chore at the end of the experiment. Basically all measurements have some uncertainty and these 'errors of observation' are estimated by using common sense and/or by knowing the precision of any instruments involved. The final uncertainty in an experiment results from the uncertainties in many measurements and the way these measurements have been combined. This 'propagation of error' is usually handled by certain rules of thumb and these are discussed in the section on analysis and covered by lectures at the beginning of your first year.

2.2.1 Errors of observation

The limited precision of a single measurement depends on the minimum scale division of the scale being used and on the definition of the indicated point (e.g. cross-hair, interference fringe, pointer etc.) or on the fluctuations of the final digit(s) of a digital meter (such instruments usually update the reading several times a second). Additionally there are ultimate limits set by the diffraction of light, by thermal vibrations of the apparatus, by the quantum behaviour of matter etc. These are met in work of the highest precision.

When any readings are taken the limit of your precision should be noted: e.g. a dimension measured with a micrometer screw gauge might be recorded as 1.32 ± 0.05 mm. Such an estimate is called a **rounding error.** Note, however, that some instruments with digital displays indicate a **truncated** value, not a rounded one. Consider carefully how well you can make a particular measurement without trying to estimate small fractions of a division. The error estimated this way should be a maximum error so that, if you are right, the true value lies within the limits given.

In addition to the limited precision of which you are conscious there are three other kinds of error likely to occur in all experiments: careless errors, systematic errors and random errors. These will now be discussed in turn.

2.2.2 Careless errors

These errors are due to definite mistakes in, for example, reading scales, counting oscillations, writing down values, keying calculators, aligning cross-hairs etc. Always repeat measurements at least once so that such mistakes are quickly identified and put right. Errors of this kind sometimes show themselves when plotting data on a graph. If one data point on the graph is clearly behaving differently from the others, go back and repeat that measurement several times. If the repeated measurement is ‘well-behaved’ then you may be justified in leaving the original data out of any subsequent analysis. However, ‘rogue’ data **must** still be recorded in your notebook.

2.2.3 Systematic errors

These errors are characteristic of the apparatus or of some bias that is consistently caused by either the surroundings or the observer. They tend to affect all readings in the same direction and cannot be eliminated or reduced by repetition and averaging. Try to anticipate possible sources of such error and plan your procedures either to eliminate them at the outset or to correct for them via a subsidiary experiment. Typically these errors arise from incorrect zero adjustment, imperfection in scale calibration, using incorrect physical data or constants in calculations, always clicking a stopwatch an instant too late and so on.

2.2.4 Random errors

These are the errors that give a spread of answers on repetition, producing a scatter around the true value. They arise from fluctuations in the surroundings (temperature, pressure, humidity, magnetic field etc.), from unavoidable variations within instruments (mechanical vibrations, electronic noise etc.) or from subjective variations in settings or readings made by the observer. It is usual to reduce the effect of these errors by repetition of readings. If the measurement can be made simply and quickly it should be repeated ten, fifteen, twenty... times in order to determine the mean value, $\overline{x}$ and the standard deviation of the sample, s:

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

$$s^2 = \frac{\sum_{i=1}^{n} \left(x_i - \overline{x}\right)^2}{n}$$

Additionally the standard error in the mean, σ_n can be calculated using

$$\sigma_n^2 = \left(\frac{1}{n-1}\right) s^2$$

As a simple rule the mean will have one more significant figure than the individual readings if at least 7 readings are averaged.

2.2.5 Precision and accuracy

In everyday language these two words are usually treated as synonyms. In the context of scientific work they have distinct meanings. Precision has to do with the number of significant figures to which a measurement can be made. It reflects the technological quality of instrumentation and the extent to which error has been minimised by statistical means. Accuracy is increased when the effect of bias is reduced by correcting for miscalibration of instruments, for design faults in mechanical and electrical equipment and for personal misjudgments. Thus:

- **accuracy** is increased if **systematic** errors are reduced and
- **precision** is increased if **random** errors are reduced.

2.2.6 Tabulation

If many similar measurements and calculations are to be made then both the experimentalist and the interested reader will be greatly assisted if the results are tabulated. This exercise needs planning:

- Prepare columns not only for readings but also for each of the calculations that are anticipated.
- Make the columns wide enough.
- It may help to use the graph paper.
- Turn the book through 90° if there are a lot of columns.
- Put a meaningful heading above every column and include the units.
- Record not only the quantity you measure but also the error in it – at least on the first row of entries. If the error is unlikely to change much during the set of readings then it may only be necessary to record it every fifth reading or so.
- If you have second thoughts and want to correct an entry then rewrite it rather than alter it.

2.2.7 Plot-as-you-go

Work out results and plot graphs as you proceed. This helps to prevent silly mistakes as results that are obviously wrong can be corrected after rechecking the measurements or recalculating the suspect item. Such corrections may not be possible if the mistake is found too late. It also helps in detecting interesting features of an experiment – a kink in an otherwise linear graph may reveal just where the interesting physics is. Guidance in drawing graphs is given below in the section on Analysis. Here we simply note that axes should be clearly labelled and scaled, and a descriptive title added.

2.3 Analysis

Whenever you calculate intermediate or final results you have to consider how errors combine together, or propagate. Any identified systematic errors should first be allowed for by correcting the measurements involved. What remain are assumed to be random errors and these are handled by two rules of thumb. We suppose that basic quantities are expressed in the form $x = \overline{x} \pm \Delta x$ where $\overline{x}$ is either a measurement, a mean value or a value derived from a graph and Δx is its associated error.

2.3.1 Rule 1: Combined error in sums and differences

if $\quad z = x + y \quad$ or $\quad z = x - y$

then correspondingly $\quad \overline{z} = \overline{x} + \overline{y} \quad$ or $\quad \overline{z} = \overline{x} - \overline{y}$

and $\quad (\Delta z)^2 = (\Delta x)^2 + (\Delta y)^2$

'Pythagoras' is applied to **absolute** errors. This equation may be extended in an obvious way to cover cases where there are three or more terms in the expression for z.

2.3.2 Rule 2: Combined error in products and quotients

if $\quad z = xy \quad$ or $\quad z = \frac{x}{y}$

then correspondingly $\quad \overline{z} = \overline{x}\,\overline{y} \quad$ or $\quad \overline{z} = \frac{\overline{x}}{\overline{y}}$

and $$\left(\frac{\Delta z}{\overline{z}}\right)^2 = \left(\frac{\Delta x}{\overline{x}}\right)^2 + \left(\frac{\Delta y}{\overline{y}}\right)^2$$

i.e. 'Pythagoras' is applied to **relative** errors. This equation may be extended in an obvious way to cover cases where there are three or more factors in the expression for z.

2.3.3 Combined error in compound expressions

If $z = \left(\frac{p}{q} + s\right)u$ for example, then the two above procedures are simply carried out a number of times: first $\frac{p}{q}$ is treated as a quotient, = *r* say; then *r* + *s* is treated as a sum, = *t* say; finally *tu* is treated as a product to give z.

2.3.4 Combined error when mathematical functions are used

If the result to be calculated involves a mathematical function of the variable measured (as in $z = x^m$, for example) the error in the result is given by

$$(\Delta z)^2 = \left(\left(\frac{\partial z}{\partial x}\right)\Delta x\right)^2$$

For the example given the relative error in z is thus m times the relative error in x.

In cases where two independent measurements are to be combined mathematically, e.g. $z = \sin x \exp y$, then partial derivatives are used and the error is given by

$$(\Delta z)^2 = \left(\left(\frac{\partial z}{\partial x}\right)\Delta x\right)^2 + \left(\left(\frac{\partial z}{\partial y}\right)\Delta y\right)^2$$

Check this expression out using $z = x + y$ and $z = xy$ to show that it is compatible with Rules 1 and 2 above. Again, the equation may readily be extended to cover the case of three or more variables.

2.3.5 Independence of variables

In all the above examples it is imperative that each independent variable is treated once and once only. This means that some expressions will have to be manipulated in some suitable way first. For example, suppose $z = (x - y)/(x + y)$ This can be transformed into $z = (1 - w)/(1 + w)$ where $w = y/x$, and finally into $z = [2/(1 + w)] - 1$. Thus only one application of the product/quotient rule is required (for Δw) followed by evaluation of Δz.

2.3.6 Drawing graphs

A good picture is worth a thousand words. The main virtues of graphs are that they can indicate the nature of the functional relation under investigation, they can highlight the discrepancy between theory and experiment, and they are useful in monitoring precision as readings are accumulated.

Graphs are **not** generally used directly to yield values for quantities of interest, rather the numbers that have been used in producing them are subjected to proper numerical analysis. This has become increasingly the case as pocket calculators with statistical packages and small computers have become available. If you use a programmed calculator to find the slope and intercept of a straight line or the standard deviation of a set of readings make sure that you understand the principles on which these facilities are based.

The essential quality of a graph is clarity. The following are the important features of a good graph:

- Make it as large as possible consistent with sensible scale factors.

- Avoid scale factors where multiples of 3 are allocated to 10 paper units, or 8 to 10 etc. They make for difficult plotting, increased error and difficulty of use.
- Label the axes clearly ('p.d. across capacitor' is preferable to 'V') and indicate the units and any powers of ten implied.
- Give the graph a meaningful title.
- Plot points as crosses (+, not x) and use the length of the lines to indicate the uncertainties.
- If you decide to sketch in a curve connecting the points, do so smoothly. If the points are on a line then calculate the slope and intercept and plot the corresponding line.

2.4 Resistor Colour Codes

The values of resistors are usually indicated by four (or occasionally five) colour bands. In four-band components, the first three bands are used to determine the resistance: the first band gives the value of the first (most significant) digit, the second gives the value of the second digit, and the third gives the power of ten to multiply the two-digit number by to obtain the resistance (i.e. the number of noughts to append). The colours have the following values:

Colour	Digit	Colour	Digit
Black	0	Green	5
Brown	1	Blue	6
Red	2	Purple	7
Orange	3	Grey	8
Yellow	4	White	9

Gold as the third band is a multiplier of 1/10.

The fourth band indicates the tolerance:

Silver indicates a tolerance of	±10%
Gold	±5%
Other colours	±percentage given in table above

Five-band codes (which are less common) are used for high precision resistors. The first three bands give digits, the fourth is the multiplier and the fifth is the tolerance.

2.5 Conclusions

When you have done as much as possible of your investigation you will have a collection of observations, notes, calculations, graphs etc. which need to be given some perspective. There are two parts to this final exercise:

First you should make a concise summary of the results that you have obtained and/or the conclusions you have reached.

Second, you should discuss the investigation in a constructively critical manner. REMEMBER: A good experiment does not necessarily mean a perfect agreement with theory. The most valuable facet of an experiment is a critical analysis of REAL data. This discussion should demonstrate that you are aware of how the experiment might be modified to be more accurate or more precise. If you think that more attention should be paid to some variable that was neglected, for instance the humidity, then **quantify** your argument, don’t just be vague. Think of how the simple theory and expected outcome of the investigation might be modified by ‘real life’ equipment and samples etc. Ask yourself what was **really** happening.

One thing that is out of place at this point is the feeble excuse: “if we’d stirred the liquid during heating we’d have got better values for the temperature” etc. This should have been thought about during the planning stage.

CHAPTER 3

WRITING REPORTS

3.1 The basic report

The results of a particular scientific investigation are useless unless they can be communicated to interested persons for evaluation and possible exploitation. There is thus a definite need for clear and concise communication. Many people, however, find it difficult to write scientific reports in a logical and precise manner. This difficulty often stems from a lack of understanding of the physical principles involved in the experiment. By concentrating one's critical faculties on these principles whilst writing a report one usually gains improved understanding.

Few discoveries or developments are truly exciting or stimulating except possibly to a few very involved people. The reporting of everyday events and results **in** an accurate and concise form is what you will commonly be called upon to do during your scientific life. Thus the formal report writing required at different times during the degree course should be regarded as a training discipline for what may well resemble your general duties as a working scientist. Consequently you should regard each formal report as a challenge to your **ability** to arouse interest in the readers and an opportunity to demonstrate your understanding, technical and literary skills to them.

Most people find it useful to employ a set format when writing reports and, indeed, scientific journals require it. In particular it is expected that the report be written in the third person. There is no universally accepted prescription for the structure of the report. The sequence that follows is probably the most widely used one.

Title

Include author’s name and date.

Abstract

This is a short statement that gives the object of the investigation and its results (including experimental uncertainties). Its purpose is to catch the eye of the person riffling through the pages of a scientific Journal allowing him or her to decide quickly if the article is relevant. It is similar to the conclusions.

Introduction

A good introduction leads the reader into the report and encourages him or her to read further. It should contain all the relevant background to the investigation so that the 'theory' section can be read with understanding.

Theory

This section should contain all the important definitions and all the principal equations used in interpreting and analysing the experiment. Brief derivations should be given if possible, particularly when a non-standard equation is used. If a derivation is lengthy it is usual to give a reference to a book or to an article in a scientific journal in which the interested reader may follow up the matter. All the basic concepts on which the experiment is based should be mentioned somewhere in this section. This section could be combined with the introduction.

Method

This part should indicate concisely the actual way in which the experiment was carried out. Particular attention should be drawn to any experimental expertise developed by the writer and to any interesting observations made. Any safety issues should be mentioned here.

Results and discussion

Results should be edited and presented as concisely as possible. If a graph is drawn then it **is** not necessary to include a table of abscissas and ordinates as well. It is also time-consuming to transcribe calculations that have been made earlier in the laboratory notebook. It is sufficient to indicate how the answer has been arrived at, by referring to the relevant equation etc.

The final result(s) and associated error(s) should be clearly stated, and the derivation of the latter indicated. The discussion may involve comparison of quantitative results with accepted values. A statement of whether these results are consistent with the accepted values should be made using precise scientific language. If the results are not consistent then the reasons for this should be discussed. Sometimes a discrepancy will be directly attributable to the limited equipment available in which case you should indicate how your experiment might be improved. Often this is the section that demonstrates the depth of understanding you have acquired of the physics behind the experiment.

Conclusions

The conclusions section is similar to the abstract in that it is frequently turned to first by the scientific browser. It should therefore state concisely the overall result of the experiment and summarise the findings of the discussion section.

References

References must be made whenever an equation, figure or idea has been obtained from an external source. References are usually cited in order to fill gaps in the exposition of a scientific article: detailed development of theory, detailed description of an experimental technique etc. The cited material is listed in its own section in a way that depends on the nature of the source: if a book then the sequence Author(s), Title, Publisher, Year of publication is used; if a journal article then Author(s), Name of journal/Volume, Page, Year; if a web page, then the URL and the date on which it was accessed should be stated. A bibliography may be included instead of or as well as the references section, and lists material that has been useful for the preparation of the report, but which does not relate to a specific item within the report.

More specific guidelines for writing reports for the first and second year laboratories can be found by following these links:

First Year:

http://newton.ex.ac.uk/teaching/resources/fyo/phy1110/files/writing_the_report.pdf

Second Year:

http://newton.ex.ac.uk/teaching/resources/au/phy2017/files/Reports.pdf

3.2 Extended experiment report (2nd Year)

This is a formal report and should appear to have been written for the information and enlightenment of someone with a similar background to yourself but without specific knowledge of the project. Further details about the report and its assessment can be found on:

http://newton.ex.ac.uk/teaching/resources/au/phy2017/extended.html

3.3 Use of English

Here are some serious points about English style!

- Make sure each pronoun agrees with their antecedent.
- Just between you and I, the case of pronouns is important.

- Verbs has to agree in number with their subject.
- Don't use no double negatives.
- Being bad grammar, a writer should not use hanging participles.
- A writer must not shift your point of view.
- Don't join sentences you've got to punctuate them.
- In letters essays and reports use commas to separate ideas in series.
- Don't use commas, which are not necessary.
- Parenthetical words however should be enclosed in commas.
- Its important to use apostrophes in everybodys writing.
- Don't abbrev.
- Check to see if you any words out.
- In the case of a report, check to see that jargonwise, it's A-OK.
- As far as incomplete constructions, they are wrong.
- In my opinion, I think that an author when he is writing should definitely not get into the habit of making use of too many unnecessary words that he does not really need in order to put his message across.
- Use parallel construction not only to be concise but also to clarify.
- It behooves us all to avoid archaic expressions.
- Mixed metaphors are a pain in the neck and should be weeded out.
- Consult the dictionary to avoid mispelings.
- To ignorantly split an infinitive is a practice to religiously avoid.

CHAPTER 4

SYNOPSES OF EXPERIMENTS

4.1 Astrophysics

CCD imaging using the Exeter observatory **astro01**

In this experiment students learn how to acquire data from an astronomical telescope, and how subsequent analysis can yield important information about stellar evolution.

4.1 Atomic and nuclear physics

Poisson and normal distributions in radioactivity **an01**

An introduction to the statistics of random events is provided in the two parts of this experiment. A Geiger-Müller tube is used to detect the natural background radiation and the emanations from a radioactive material. Each provides a source of random events, which can be used to demonstrate the Poisson and normal probability distributions.

Franck-Hertz experiment **an02**

In this experiment, neon atoms are excited from the ground state by bombardment with electrons. It is found that energy is transferred from an electron to a neon atom in discrete amounts. When the neon atoms decay back to their original state they emit visible light, which provides an intuitive picture of the energy transfer. This experiment was originally conducted in 1914 and yielded results inexplicable by classical physics. It thus helped pave the way to the development of Quantum Mechanics.

Detecting radioactivity **an03**

This investigation consists of two experiments looking at methods of detecting radioactivity. In the first experiment, the ionisation of air by radioactivity is measured. In the second, the characteristics of a Geiger–Muller counter-tube are studied.

Compton scattering **an04**

A well-collimated beam of 662 keV photons from a ^{137}Cs source is scattered from an aluminium target. The energy of the scattered photons as a function of the scattering angle is measured using a scintillation counter. The object of the experiment is to verify the expected theoretical dependence of energy on angle, of this highly relativistic scattering process.

Alpha particle investigations **an06**

An α-particle source is mounted in a small vacuum chamber (a Rutherford chamber) at a fixed distance from a semiconductor detector. The energy spectrum of the α-particles is measured in vacuum, and their energy loss in air, and passing through thin metal foils is investigated. The α-particle peaks from a ^{226}Ra source are used to measure the age of the sample.

Electron-positron annihilation **an07**

Positrons emitted from a ^{22}Na source are slowed down in the source and annihilate in collisions with electrons. It is predicted that the two photons produced in this annihilation should be emitted simultaneously, should both have energy 0.511 MeV and should be emitted from the source in opposite directions. Two scintillation counters with coincidence electronics are used to verify these predictions.

Wave particle duality: optical and electron diffraction **an08**

In this experiment you will investigate wave-particle duality, the cornerstone of quantum mechanics. Classically the phenomenon of diffraction is only associated with waves. However, the diffraction of electrons and neutrons was demonstrated in the 1920 after de Broglie suggested that particles could behave as waves. These experiments were some of the most powerful arguments in favour of quantum mechanics at the time.

Rutherford scattering **an09**

Introduction to scattering theory by performing Rutherford's famous experiment, scattering alpha particles off heavy nuclei. In this experiment the scattering rates for gold and aluminium are measured and the atomic number of aluminium is determined from the experimental results.

X-ray physics **an10**

In the first investigation a simple X-ray diffractometer and Geiger-Müller counter are used to investigate the Bragg reflection of molybdenum K_α and K_β X-rays from a sodium chloride crystal. The object is to verify that the diffraction peaks are those appropriate for a crystal with a face-centred-cubic lattice and to measure the cubic lattice parameter. The second part is a study of the X-ray spectrum itself: its dependence on X-ray-tube voltage and current, and the relationship between the minimum wavelength present in the spectrum and Planck's constant.

Magnetic resonance **an11**

Electron or nuclear spins subjected to a magnetic field have two discrete energy levels corresponding to the spins aligning and anti-aligning with the field. When photons matching this energy splitting impinge on the spins, they are resonantly absorbed.

This phenomenon is investigated in two separate experiments for nuclear spins (in hydrogen nuclei) and for electron spins (in an organic compound, DPPH). In both cases the photons have radio frequencies.

Introduction to X-rays **an12**

This experiment is an introduction to X-rays. Experiments involve measuring the absorption and diffraction of X-rays in a choice of materials. In particular, the lattice spacing of NaCl is identified and compared with the known value.

Gamma ray spectroscopy **an13**

In this experiment the spectra of gamma rays emitted by a variety of radioactive sources are investigated. The attenuation of gamma rays by metal shielding is measured, and the weak natural radioactivity of potassium chloride is studied.

The Zeeman effect **an14**

The Zeeman effect is the splitting of atomic energy levels, and their resulting spectral lines, due to an external magnetic field. In this experiment, the spectrum of cadmium is investigated, using a Fabry-Perot etalon to resolve the fine structure in its spectrum resulting from the Zeeman effect, and its dependence on the orientation of the magnetic field.

Radioactive decay and half-life **an15**

Introduction to radioactive elements and radioactive decay. You will learn more about the half-life of radioactive elements, and as an experiment, you will measure the decay of the metastable isotope Be-137. The half-life will be calculated and compared with the known value.

Ionisation chamber **an16**

The ionization chamber and telescopic cylinder are used to demonstrate and to examine radioactivity. In particular, they can be used to determine the ionizing effects of radioactive materials, the half-life of thorium emanation and the range of alpha particles. Here you will have an opportunity to use ionization chamber for studies of alpha particle radiation.

4.2 Electricity and Magnetism

Current balance em01

A current may be measured by finding the force exerted on a coil of wire carrying it in the presence of a magnetic field and invoking the fundamental definition of the ampère. In this experiment theory and experiment are compared and a simple system investigated for the absolute measurement of current.

Charge and discharge of a capacitor through a resistor em02

Both charge and discharge of a capacitor C through a resistor R are measured and theory compared with experiment. The time-constants CR of the circuits used are determined. A digital voltmeter capable of making serial measurements is used.

Owen's (AC) bridge em03

In this experiment a simple bridge network is used to measure the inductance and capacitance of a circuit element. Since this is an alternating current measurement it is important to note that two conditions have to be satisfied for balance.

AC circuits em04

The input-output relation is determined for simple circuits using a resistor, a capacitor and/or an inductor, with both steady-state (sinusoidal) and transient (voltage step) inputs. Lissajous figures are also investigated.

Series-resonant LCR circuit em05

The resonant behaviour of a series inductor-capacitor-resistor circuit is investigated by plotting resonance curves for various values of resistance. Values for the circuit magnification factor Q are determined in two different ways and compared with theory.

Equipotentials em06

This experiment illustrates how equipotential lines for a two-dimensional system of electrodes may be obtained experimentally. The electrodes are placed in a weakly-conducting liquid (tap water) and a probe electrode is used to plot lines along which the potential in the liquid has predetermined values intermediate between the electrode potentials.

The Hall effect em07

The Hall effect involves the production of a transverse potential difference in a specimen, which carries a longitudinal current in a magnetic field. In this experiment the effect is investigated and the Hall coefficient (corresponding to the magnitude of the effect) is determined for a specimen of semiconductor.

Rectification and smoothing em08

The low-voltage DC supply needed for many applications is conveniently derived from the AC mains. In this experiment a transformer is used to reduce the mains supply to low voltage AC. Rectification and smoothing circuits then convert AC to DC. Their effectiveness is measured by comparing the amplitude of the unwanted output ripple (i.e. voltage fluctuation) to the magnitude of the DC component in the output.

The fine-beam tube em09

Electrons, accelerated through a potential difference in an electron gun, are launched into a glass bulb and constrained to move in a circular path by an applied magnetic field. Gas at low density in the bulb renders the beam visible and keeps it narrow by ‘gas focusing'. The object of the experiment is to obtain a value for e/m from measurements of the accelerating voltage, the magnetic field and the radius of the electron orbit.

Experiments with microwaves em10

When total internal reflection of light occurs, for instance inside a glass prism, there exists a (non-propagating) disturbance *outside* the reflecting face of the prism. The intensity of the disturbance falls off exponentially with distance, on a scale related to the wavelength of the light. In the first part of this experiment, microwaves, electromagnetic waves with much larger wavelengths than those of visible light, are used to demonstrate this effect on a more convenient length scale.

Helical molecular structures can induce rotation of the plane of polarisation of incident light: they are 'optically active'. The second part of this experiment illustrates this by using a set of copper coils and illuminating them with microwave radiation. The rate of rotation can be determined by increasing the number of layers of coils between the source of radiation and the detector. Some comparisons with theory are possible.

The Hall effect in an extrinsic semiconductor em11

If a conductor carrying a current i is placed in a magnetic field B a potential difference V_H develops across the conductor in a direction perpendicular to both the current and the magnetic field. Measurement of this p.d. as a function of B for fixed i, and as a function of i for fixed B, gives information on the density of the charge carriers and their mobility.

Series-parallel RLC circuit em12

In this experiment measurements are made on a series-parallel *RLC* circuit under both pulsed and sinusoidal sources of potential difference. The results are compared with the standard mathematical predictions. The experiment is open-ended and a variety of extensions may be explored.

Millikan experiment em13

This is the famous experiment performed originally by R. A. Millikan in 1910, which demonstrate the quantisation of electronic charge. You will investigate the behaviour of charged oil droplets in a vertical electric field. The measurements will confirm the discrete nature of the elementary charge accumulated on the droplets ($Q = ne$, where e is the charge of electron and n is an integer).

Chaos em16

Chaos is a phenomenon associated with driven non-linear systems. It gives rise, for instance, to the 'butterfly effect' in meteorology. In the experiment a simple non-linear electronic circuit consisting of an inductor, a capacitor and a diode is driven into its chaotic regime by an external oscillator. In addition to chaotic behaviour, other characteristics of non-linear systems, such as bifurcation (period-doubling) are observed.

Laws of radiation em17

All bodies emit thermal radiation, the total irradiance of which is expected to be proportional to temperature raised to the fourth power. This experiment tests this prediction and examines the effects of surface texture and quality on the irradiance.

Superconductivity em18

An introduction to superconducting materials. In this experiment, you will have opportunity to experiment with high-temperature superconductors, such as YBCO. Operating at the boiling point of liquid nitrogen, the Meissner effect will be explored (including an observation of a levitating magnet). The temperature- and field-dependences of the superconducting current will also be measured and analyzed.

Ferromagnetic hysteresis, dia-, para- and ferromagnetism. em19

Magnetic properties of many materials can be classified into three major groups: dia-magnets, para-magnets and ferro-magnets. In this project you will have opportunity to get familiar with some of the typical materials in each of these classes. You will learn about magnetic torque measurements and use the technique to measure the magnetisation of three given metals. A measurement of ferromagnetic hysteresis will also be explored to understand the magnetic field dependence of the magnetisation, key to the operation of magnetic storage devices such as hard disks.

Force in a magnetic field **em20**

This experiment explores one of the most fundamental properties of electromagnetism, the Lorentz law. In a series of measurements the Lorentz force will be measured in different configurations of magnetic field and current. Through variation of the current, the external magnetic field of the electromagnet will be measured and calibrated against the driving current of the coil.

4.3 General physics

Power transfer with a solar cell **gn01**

If a source of electrical power is connected to a resistive electrical load, the power delivered to the load depends on the load resistance. Maximum power transfer is obtained with a particular value load. In this experiment a comparison is made between the power transfer from source to load for (a) a conventional voltage source, such as a battery, and (b) a solar cell.

Graph plotting and error analysis **gn02**

This experiment is a gentle introduction to graph plotting, both by hand, and using the computing packages available. In addition, some simple exercises are provided in error analysis. It is strongly recommended that all first-year students do this practical, as early in the year as possible.

Automating experiments using LabVIEW **gn03**

This is an introduction to computer-automated physics experiments, using the commercial data acquisition software package LabVIEW, on a PC. The three parts of the practical comprise: a hands-on LabVIEW tutorial; use of pre-programmed “virtual instruments” that mimic the behaviour of standard laboratory instruments; and the design of a simple virtual instrument to plot the current vs. voltage characteristics of electronic components.

4.4 Mechanics and properties of matter

Bar and torsional pendula **me01**

In the first of two investigations a pendulum, consisting of a steel bar supported on a knife-edge, is used to find a value for the acceleration due to gravity, g, and the radius of gyration, k, of the bar about an axis through its centre of gravity. Two graphical methods for determining g are used and the value of k is compared to that obtained theoretically. In the second investigation the torsional oscillations of a brass disc attached to steel wires of various diameters are studied. In addition the effects of moment of inertia on oscillation frequency are determined. The method of dimensional analysis is used to obtain results in this study.

Flow through a tube **me02**

A fluid can flow according to one of two flow régimes: laminar or turbulent. In this experiment air is blown through a tube and both régimes can be observed by varying the flow speed and hence the pressure drop between the ends of the tube.

One-dimensional motion **me03**

Fletcher’s trolley is the classical apparatus for investigating linear translational motion. In this experiment using a single-line CCD video camera you will have opportunity to study a variety of linear motions. The time dependence of velocity in linear and oscillatory accelerations under the action of the gravitational force will be measured and analyzed using the basic principles of mechanics.

Air resistance **me04**

Measurements on a falling table-tennis ball lend themselves to a numerical (computer) calculation of air-resistance parameters.

Determination of the Young modulus **me05**

A number of specimens of materials that can be obtained in the form of slender rods (glass, aluminium, brass etc.) are mounted horizontally and made to bend under the application of weights. From the dependence of the depression produced on the weight it is possible to determine the Young modulus for each materia

Rolling sphere on a rotating turntable **me06**

This experiment explores the response of a moving body to an applied force. The body is a large ball, which is placed on a rotating glass plate. The orbital frequency of the ball and its drift velocity across the plate are studied as a function of the rotation frequency and the angle of tilt of the table.

The Euler strut **me07**

This experiment explores the behavior of a straight bar when it is clamped vertically at its lower end and loaded at its upper end. The bending of the bar and its frequency of oscillation under different loads provide data for comparison with theory.

The unstable bucket **me08**

The behavior of a ‘bucket' as it is filled to different levels with water is to be investigated. The conditions for stability of the bucket can be studied and the results compared to those given by theory. A computer program is available to evaluate the angles of stability expected in different situations.

Rotational dynamics **me09**

This is an investigation of rotational motion using a turntable floating on a cushion of air to minimise friction. The phenomena of angular velocity, angular acceleration, conservation of angular momentum and rotational kinetic energy, and the rotational equivalent of Newton’s second law are explored.

Determining the gravitational constant **me10**

In this experiment the gravitational constant G is measured using an extremely sensitive torsion balance. The attraction of two masses leads to a small rotation of the balance which can be detected using an ‘optical lever’, the deflection of a laser beam projected over a large distance. The rotation can then be used to calculate G.

Coupled pendula **me11**

The aim of the first part of this experiment to study properties of a simple pendulum, how its resonant frequency depends of length and how the oscillations are related to the acceleration due to gravity, g. The aim of the second part of the project is to study two weakly-coupled pendula, finding their normal modes and observing the beats of two close frequencies.

4.5 Optics

Diffraction **op03**

The diffraction pattern produced by a single slit is one of the commonest and most fundamental diffraction patterns. The aim of the first part of this experiment is to measure the intensity variation across the diffraction pattern and compare it with theory, for various different widths of slit. In the second part, double-slits are investigated.

The Rayleigh refractometer **op04**

In this instrument, interference occurs when two light beams are recombined which have passed through two separate tubes containing gas. By measuring changes in the interference pattern as the pressure of the gas in one of the tubes is varied, the refractive index of the gas may be determined. If the gas in one tube is replaced by another, the refractive index of the new gas may be determined relative to the reference gas.

Chromatic resolving power **op05**

Resolving power is one of the basic concepts of optics. Chromatic resolving power concerns the ability to distinguish two spectral lines, which differ by a small amount in wavelength. Two dispersive systems are used, a prism and a diffraction grating. In both cases, an aperture restricts the width of the beam of light falling on the instrument; this width is adjusted until a spectral doublet can just not be resolved.

The helium-neon laser **op06**

In this experiment, a helium-neon laser is built from its component parts: a plasma tube and two mirrors and optimised. The way in which the width of a laser beam varies with distance from the laser is studied. The experiment needs very careful adjustment and lining up, but if this is done, good results can be obtained.

Scanning Fabry-Perot interferometer **op08**

As the separation of the plates of the interferometer is varied, the multiple-beam interference pattern can be scanned by a detector. The aim of the experiment is to compare the shape of this interference pattern with the one expected theoretically. Two parameters of the pattern, the finesse and the contrast, are investigated to see whether their values are self-consistent. The experiment is repeated using an expanded beam, to see whether this makes any difference to the results.

Faraday rotation **op09**

The rotation of the plane of polarisation of light as it passes through a material parallel to an externally applied magnetic field is measured. The angle of rotation should be proportional to field strength and to length of path in the field. The applied field is modulated by means of an AC signal on the coil, which enables the rotation angles to be measured by a null method.

Experiments with polarized light **op10**

The experiment is designed to illustrate the concepts of plane, circular and elliptical polarisation of light. A quarter-wave plate and half-wave plate are used to do this, and students should satisfy themselves that they are able to explain theoretically the results obtained.

The Michelson interferometer **op11**

The Michelson interferometer is one of the most important instruments in optics, and still finds many applications today in research. In this experiment, after preliminary familiarisation with the various types of interference fringes, which can be obtained with the instrument, it is used to show the relation between length scales and the wavelength of light. With care, very accurate results can be obtained. The instrument is also used to show how the wavelength separation of a spectral doublet can be determined.

Velocity of light **op14**

In this experiment the velocity of light is measured in three media: air, perspex and water. The method is a time-of-flight measurement, using a modulated laser diode as the light source.

4.6 Soft-matter physics

Elastic properties of soft materials **sm01**

This is a study of the mechanical properties of rubber-like materials analogous to elastic biological polymers. There are two possible mechanisms for elasticity: energy elasticity (exhibited by most crystalline solids, e.g. a metal spring), and entropy elasticity (exhibited by many amorphous polymers). The mechanism in these materials is investigated by measuring the effects of temperature on their elasticity.

Physics of soap bubbles **sm02**

This experiment is an investigation of how surface tension influences the shape of liquid films. The shape of the soap bridge formed between two circular hoops is measured and compared with theory which predicts that the surface energy of the film is minimised when the shape is a catenary.

Investigating capillary and gravity waves **sm03**

Two forces are responsible for the waves at a liquid-gas interface: gravity and surface tension. In this experiment, the velocity of waves on the surface of water is measured as a function of their wavelength, in order to investigate the contributions of these two forces, and hence to determine the surface tension of water and the acceleration due to gravity.

Scanning Tunnelling Microscope (STM) **sm04**

This technique is currently one of the most commonly used research tools for studies of nanostructures, nanomaterials and surfaces. Here, by using STM you will study the topography of certain crystals, and also investigate the surface quality of patterned nanoscopic structures artificially fabricated by electron-beam lithography.

Viscosity **sm05**

A body moving in a fluid is acted on by a frictional force in the opposite direction of its velocity. The magnitude of this force depends on geometry of the body, its velocity, and the internal friction of the liquid. A measure of this friction is given by the dynamic viscosity. In this experiment, by using a free falling ball setup, you will investigate the dynamics of a spherical object in different liquids. From the analysis of the translational motion the values of the dynamic viscosity will be derived and compared with those available from the literature.

4.7 Thermal physics

Latent heat of liquid nitrogen **tp01**

The method used in this experiment for the determination of the latent heat of vaporisation of liquid nitrogen is based on the electrical heating of a known mass of material. The student is encouraged to make careful measurements and make an accurate assessment of errors.

Propagation of temperature waves in a bar **tp02**

Thermocouples are constructed, calibrated and then used to measure variations in temperature along a lagged aluminium rod heated at one end and open to the atmosphere at the other. The heating is applied in pulses. An approximate solution to the distribution of temperature with time and distance along the bar is used to compare theory with experiment.

Gas Laws **tp03**

In these classic experiments of thermodynamics you will investigate the well-known properties of ‘ideal’ gas. The measurements will include the Boyle-Mariotte’s law (volume against pressure), the Gay-Lussac’s law (volume against temperature) and the Amontons’ law (pressure against temperature).

Hot-air engine **tp05**

The hot-air engine (invented by R. Sterling, 1816) is the oldest thermal engine, representing a fundamental thermodynamic system for generating a cyclic mechanical motion. Its original principles are still used in most modern engines utilised in a great variety of vehicles (including ordinary cars, trains, planes etc.). This experiment demonstrates the principles of operation, and will get you familiar with the four components of the thermodynamic cycle.

Measuring the efficiency of a heat engine **tp06**

A heat engine does extracts heat from a fixed-temperature reservoir, converts some of it to mechanical work, transferring the rest to a reservoir at a lower temperature. The second law of thermodynamics imposed a limit on the efficiency of this process. In this experiment, the efficiency of the hot-air engine running as a heat engine is measured and compared with the second law of thermodynamics. In a preliminary measurement the frictional losses of the machine are determined so that the effects of these can be accounted for when the efficiency is measured.

4.8 Waves and vibrations

Ultrasonic Waves **wv01**

In this experiment the fundamental properties of waves are studied by means of ultrasound. In a two-part experiment you will investigate the principles of interference and reflectivity of acoustic waves. You will also investigate different wave effects, such as beating, and learn about applications of ultrasound. In particular, the experiments will look at the principles of an echo sounder.

Speed of sound in air **wv02**

A closed copper tube fitted with a sound transmitter and reflector is used to set up standing waves in the tube. By moving the transmitter relative to a receiver, which responds to changes in air, pressure the speed of sound in air can be determined.

Vibrational modes of a solid **wv05**

Longitudinal and torsional modes are generated in a nickel rod using the phenomenon of magnetostriction. Standing waves are created and the wavelengths of these are measured for different frequencies of excitation. Two families of frequencies can be obtained in this fashion from which the velocities of the longitudinal and transverse waves can be evaluated. The latter permit the values of the Young modulus and the rigidity modulus to be inferred.

The dispersion curve for a linear lattice **wv07**

This experiment investigates the electrical analogue of a linear lattice. It consists of two sequences of capacitors and inductors arranged to mimic the behaviour of monatomic and diatomic linear lattices. Careful measurement of the resonance frequencies for the two networks reveals a single curve for the frequency versus mode number plot in the monatomic case and two curves in the diatomic case. A possible extension of the experiment shows how a ‘local mode' may arise if the lattice is interrupted by an alien atom.

Driven harmonic motion **wv08**

Harmonic motion is an important phenomenon since vibrations and oscillations in a wide range of physical systems can be treated as harmonic when the amplitudes are sufficiently small. The equations governing it are found throughout physics: in classical mechanics, electromagnetism and quantum mechanics. This series of experiments makes use of the Pasco driven harmonic motion analyser to examine the behaviour of a simple system (consisting of a mass on a spring) as its many variables, such as spring constant, mass, driving frequency, amplitude and damping coefficient, are altered.