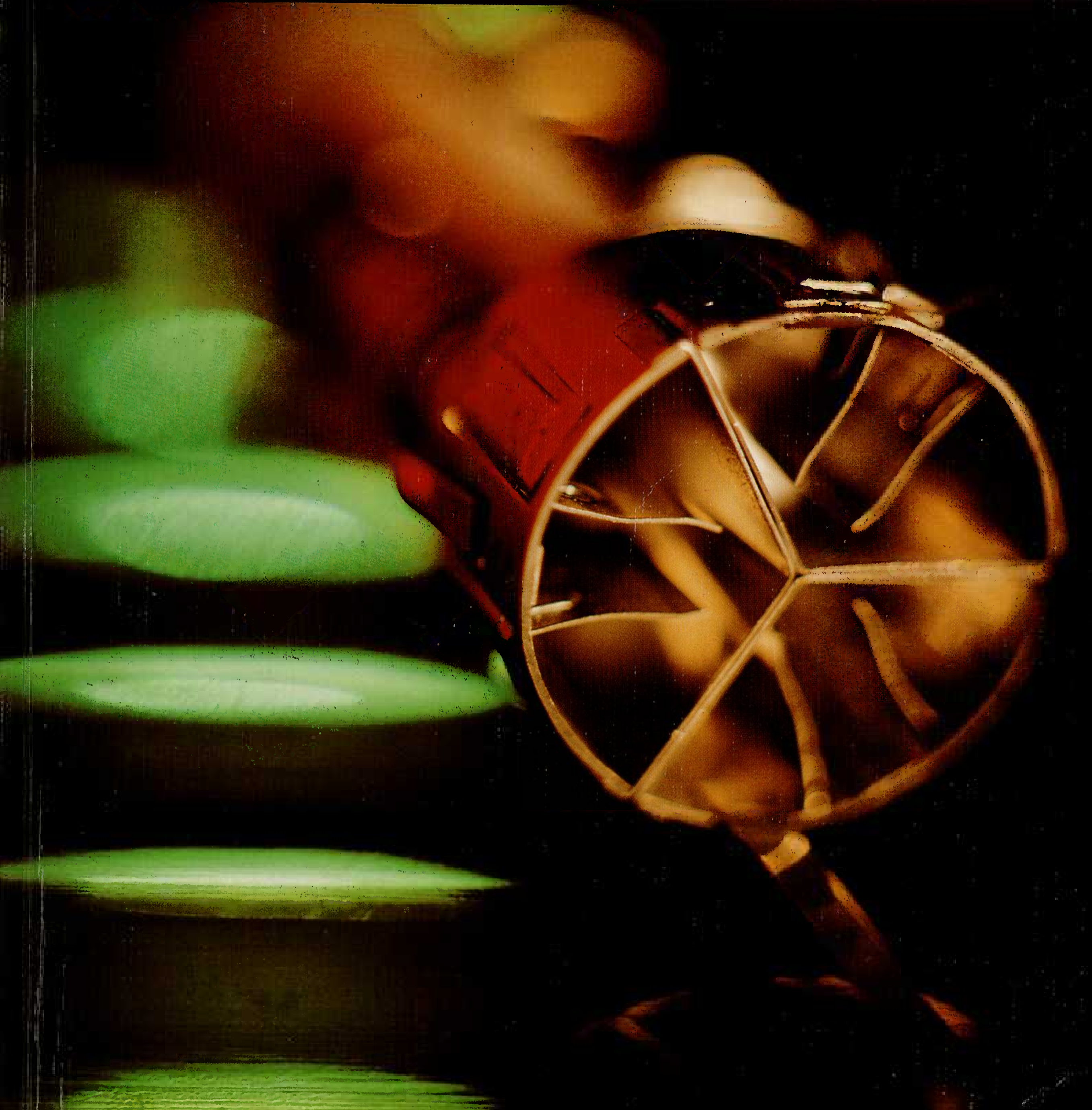
REVISED

NUFFIELD ADVANCED SCIENCE

PHYSICS

STUDENTS' GUIDE 1 UNITS A to G



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PHYSICS

STUDENTS' GUIDE 1

UNITS A to G

Revised Nuffield Advanced Science

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The Nuffield–Chelsea Curriculum Trust is grateful to the authors and editors of the first edition:

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REVISED NUFFIELD ADVANCED SCIENCE
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An electron gun, part of a television picture tube or cathode ray tube. When electrons from the gun strike the phosphor on the screen the screen emits light, so building up a visible image.

Paul Brierley

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FOREWORD

When the Nuffield Advanced Science series first appeared on the market in 1970, they were rapidly accepted as a notable contribution to the choices for the sixth-form science curriculum. These courses were devised by experienced teachers working in consultation with the universities and examination boards, and subjected to extensive trials in schools before publication and they introduced a new element of intellectual excitement into the work of A-level students. Though the period since publication has seen many debates on the sixth-form curriculum, it is now clear that the Advanced Level framework of education will be with us for some years in its established form. That period saw various proposals for change in structure which were not accepted but the debate to which we contributed encouraged us to start looking at the scope and aims of our A-level courses and at the ways they were being used in schools. Much of value was learned during those investigations and has been extremely useful in the planning of the present revision.

The revision of the physics course under the general editorship of John Harris has been conducted with the help of a committee under the chairmanship of K. F. Smith, Professor of Physics, University of Sussex. We are grateful to him and to the committee. We also owe a considerable debt to the Oxford and Cambridge Schools Examinations Board which for many years has been responsible for the special Nuffield examinations in physics and to the Assistant Secretary of the Board, Mrs B. G. Fraser, who has been an invaluable adviser.

The Nuffield–Chelsea Curriculum Trust is also grateful for the advice and recommendations received from its Advisory Committee, a body containing representatives from the teaching profession, the Association for Science Education, Her Majesty's Inspectorate, universities, and local authority advisers; the committee is under the chairmanship of Professor P. J. Black, educational consultant to the Trust.

Our appreciation also goes to the editors and authors of the first edition of Nuffield Advanced Physics, who worked with Jon Ogborn and P. J. Black, the project organizers. Their team of editors and writers included: W. Bolton, R. W. Fairbrother, G. E. Foxcroft, Martin Harrap, John Harris, A. L. Mansell, and A. W. Trotter. Much of their original work has been preserved in the new edition.

I particularly wish to record our gratitude to the General Editor of the revision, John Harris, Lecturer at the Centre for Science and Mathematics Education, Chelsea College, and a member of the team responsible for the first edition. To him, to E. J. Wenham, Consultant Editor of the revision, and to the editors of the Units in the revised course – all teachers with a wide experience of the needs of students and of the current state of physics education – Roger Hackett, Nigel Wallis, David Grace, Mark Ellse, Charles Milward, Trevor Sandford, Paul Jordan, Peter Harvey, Maurice Tebbutt, David Chaundy, Wilf Mace, Stephen Borthwick, Peter Bullet, and Jon Ogborn, we offer our most sincere thanks.

I would also like to acknowledge the work of William Anderson, publications manager to the Trust, his colleagues, and our publishers, the Longman Group, for their assistance in the publication of these books. The editorial and publishing skills they contribute are essential to effective curriculum development.

K. W. Keohane,
Chairman, Nuffield–Chelsea Curriculum Trust

ABOUT THE COURSE AND ABOUT THIS BOOK

At the beginning of a new course in physics we think you should know something about its special features, the ways in which it may be different from other physics courses at A-level, and the reasons for these differences.

Physics, and the world with it, are changing so fast that no one can tell what aspects of physics you will use in, say, ten years' time: however, one can be pretty sure that there are some basic ideas that will be relevant to the new problems of tomorrow. We have tried to build the course around these basic ideas.

A-level physics courses do not all cover exactly the same topics. So you will find some topics in this course that do not appear in other A-level courses. You will also find that this course does not include some items that are included in others. But you should know that there is a core syllabus which is common to all A-level physics courses, including this one. The core of physics which universities and other institutions regard as essential to further study is covered in this course.

You will study fewer physics topics in this course than you would in most other A-level courses because we believe that it is more important to have a good understanding of some basic ideas and to be able to use them confidently, than to know less about more. Those who understand their physics are the ones who can offer sensible, relevant ideas that would help towards clearing up a problem.

The course aims to show you what doing physics is like, and this is another reason for encouraging plenty of discussion of problems, for that is the way physicists work. To use physics successfully and to understand what it can, and what it cannot do, it is important to know about such things as how theories, models, experiments, and facts fit together. Physicists also guess, estimate, and speculate, and you will be asked to do these things too.

But physics is more than facts and theories: it has practical value and through its application in science and technology it has social and economic effects on the way we live. Some of the Units in the course emphasize this aspect of physics, and in most of the Units there are questions and reading about how physics can be used in engineering and technology.

This course regards students as active, creative people making their own sense out of the physical phenomena they meet. The alternative view of students as passive recipients of knowledge, dry sponges absorbing facts and formulae provided by a teacher or text book is *not* one we have adopted in designing this course.

You will find that this emphasis on activity takes many forms: you will do many experiments – and sometimes be asked to demonstrate them to others; you will read from a variety of sources including text books, magazines, and special articles – and you may be asked to give a written or verbal report on what you have found out; you will do two independent investigations, in which you plan and carry out your own work on a topic of your choice for a couple of weeks. And there should be plenty of opportunities to *talk* about the physics you are learning – because that is probably the best way to find out how well you understand it.

We think that to learn effectively, now and in the future, certain skills are very valuable, and in designing the course we have sought ways of helping you develop skills of various sorts: including experimental, communication, and mathematical skills.

This *Student's guide* is not the 'text book' of the course. It is important to realize that you must keep your own notes and records of the course as you go along. You will also need access to other sources: text books and reference books in the school or college library, data books, journals, magazines, and so on.

More about this book

The course is divided into twelve Units. Units A to G are covered in this book, Units H to L in *Students' guide 2*. For each Unit there are:

Summaries These are very short and are not intended to do more than the name suggests. They only *summarize* the most important ideas of each part of the course. They do not show you how results are derived; they do not give full explanations of methods, or evidence for the facts stated. You can follow some of these derivations by working through questions in the book; some of the evidence is provided by the experiments and demonstrations suggested for the course. You will find references in the margin to these questions and to the practical work.

These summaries will be most useful to you *after* you have studied a particular part of the course in class, and for revision. We hope they will help you remember what some of the key ideas are, and what the experimental evidence and theoretical basis for them are.

Readings As part of most Units we have included a few short passages which depend on the ideas developed in the Unit. We have included questions about them, to help you develop the skill of reading with a purpose, which is one of the aims of the course.

Laboratory notes You will find brief notes on most of the experiments and demonstrations suggested for the course – notes, not instructions. Their purpose is to show what equipment is needed, how to set it up, and to suggest some questions which can be answered, or some observations which can be made with it.

Home experiments Learning and doing science is not something to be confined to school or the laboratory. So in some of the Units we have included suggestions for practical activities that you can do at home.

Questions With each Unit we have included a large number of questions – more than any one student will be able to do while studying the Unit. There are various kinds of questions. Each has a letter as well as a number: the letter tells you what kind of a question it is.

The code is:

I Introductory questions: These are questions which you should be able to do confidently *before* you start the Unit. These questions make use of the simpler ideas which the Unit takes as its starting point.

L Learning questions: Many of the derivations of standard results, formulae, relationships, etc., are presented in the form of questions. These questions are intended to help you learn new physics rather than test what you have learned before.

P Practice questions: You should find these relatively simple and straightforward. They are intended to give you practice in using the new ideas you have learned in fairly simple situations.

E Essay, estimation, and discussion questions: A more open category of question to encourage a different kind of thinking and writing. There are no right and wrong answers to these.

R Review and revision questions: As the name suggests, these are examples of the kind of questions that you should be able to answer at the end of the course. This kind of question may cover work from more than one Unit. Several of them are taken from past examination papers.

Formulae, relationships, data, and symbols are gathered together at the end of each *Students' guide.*

Experimental work The short passage on pages xii to xvi of this book makes some general points about doing experiments, taking measurements, and interpreting results. You will find it useful to refer to it from time to time throughout the course.

So there are many things in this *Students' guide* that you should find helpful during the course. But it is important to realize that you will need to use other sources as well, and to keep your own notes of the work as you go along.

More about skills

Some of the useful skills we hope the course will help you acquire include:

Experimental skills: ability to use a range of modern tools used in physics; ability to design effective experiments; understanding of the factors which affect the reliability of measurements.

Communication skills: ability to extract and make use of information from technical articles; ability to present technical arguments; ability to convey technical ideas to a 'lay' reader; ability to discuss critically and constructively experimental or theoretical work, either your own or a colleague's. The course will give you opportunities to practise these communication skills both verbally and in writing.

Mathematical skills: algebraic manipulation; handling scientific notation quickly and efficiently; giving useful rough estimates and dealing sensibly with approximations; graphical work – use of graphs to display data, recognition of some important functions, interpretation of the physical significance of the slopes and areas under some graphs; using the idea of rate of change in many experimental situations; ability to discuss the exponential function in a number of different situations; numerical methods of solving equations, which lead into computer methods.

The course itself

This Revised Nuffield A-level physics course is the result of the combined efforts of many teachers with considerable experience of teaching the original course. One of the main reasons that we want to offer you some physics is that we like the subject and get excited about it. So we hope you enjoy it too.

The Editors

EXPERIMENTAL WORK

Wilf Mace
King Edward VII School, Sheffield

Physics is about how the world works, and the only way to find how it works is to observe it. This is why observation and measurement are vital to physics. As with all techniques, experimenting has its own set of particular skills, and these notes are to draw your attention to a number of things that need to be borne in mind in practical work.

Uncertainty

Nothing can ever be measured exactly. Even if an object apparently reads exactly 15 divisions against a millimetre scale, we know that if it were 14.98 mm or 15.02 mm we simply wouldn't be able to tell the difference: there is always an *uncertainty* in every measurement we make, however carefully we work, and the size of the uncertainty is governed by the instrument we are using. We therefore need to consider our instruments rather carefully, in order to make the best possible use of them.

Characteristics of measuring instruments

The variety of instruments and techniques at our disposal have some rather obvious properties, and also some less obvious ones that may be equally important. There is a vocabulary about this, and a glossary of the most important terms is given below. We don't suggest you should 'learn' these at the start, but as your experience grows you will find that the ideas they represent keep cropping up, and you will come to appreciate the kinds of situation in which they need to be taken into consideration.

Range: This term has the obvious meaning. Typical values would be 0–100 mA for a meter, -10 to $+110$°C for a thermometer, and so on.

Resolution: This refers to the smallest change (increment) that can be detected. For instruments with scales (micrometer, ammeter, thermometer, etc.) it is normally taken to mean the value indicated by one smallest scale division, though in practice, fractions of a scale division can often be judged quite reliably. For digital readout instruments it means the value of one unit in the last digit. Manufacturers often express resolution as a percentage of the range. Thus a typical school microammeter may have a range of 100 μA, with 50 divisions: this constitutes a resolution of 2 μA or 2 % (of the range). But note that resolution is by no means the only factor which may affect the uncertainty of a measurement: see, for example, *repeatability*, below.

Sensitivity: This refers particularly to instruments such as the light beam galvanometer, and the oscilloscope, where a scale of mm or cm is provided and may be made to represent different ranges of values. Statements of sensitivity take the form '$16.2\,\mathrm{mm}\,\mu\mathrm{A}^{-1}$' or (in inverse form) '$0.2\,\mathrm{V}\,\mathrm{cm}^{-1}$'.

Response time: A light beam galvanometer responds rather slowly to changes of voltage; an oscilloscope responds within a small fraction of a microsecond. The rapid response is obviously very necessary for following high frequency fluctuations, as in electronics, but there are situations when a long response time is advantageous. In a ratemeter for radioactivity measurements a long response time is deliberately built in, so that the pointer, instead of flickering at every count, tends to show a fairly steady averaged value of the count rate.

Response time can be an important property of transducers too. Temperature-measuring instruments tend to be very sluggish, so that rapid fluctuations of temperature are difficult to measure reliably. Some types of photocell, too, have response times of an appreciable fraction of a second, and may be unsuitable for fast photographic work.

Accuracy: Given an ammeter stated by the manufacturer to have a range of 5 mA, we tend to assume that this figure is reliable: similarly with metre rules, stopwatches, frequency generators, and indeed all scaled instruments. This is what we mean by accuracy. Sometimes instruments are stated to conform to some British Standard Specification (B.S.S.), and that is a guarantee that they are accurate to within some specified limit. In school laboratories, accuracy has sometimes to be taken on trust, though one learns to notice that some makes of meter, for example, tend to be consistent with one another and so can be hoped to be accurate, or perhaps that 10 g slotted masses can disagree by 0.4 g and therefore some of them must be inaccurate by at least 0.2 g.

Linearity: A meter may be extremely accurate at one point, but inaccurate over other parts of its scale: this is referred to as a fault in linearity, since a graph showing the true current against the scale reading would not be a straight line. In high accuracy work it is often necessary to draw a calibration curve to use in conjunction with an instrument to correct readings for non-linearity.

Repeatability: Experimental situations are very often not as simple as we would like to make them. Pointers may be sticking slightly, a bad contact may make a current change slightly, a clamp may not be sufficiently rigid, we may handle a micrometer clumsily: the list is endless. But effects like these are very easily missed unless we go out of our way to look for them, so the first thing we should do with *any* reading is to check that it is repeatable. Whatever the 'theoretical' resolution of an instrument may be, the actual uncertainty in a measurement must be judged in terms of repeatability.

Systematic error: Some factor in an experimental situation may cause a whole series of apparent values to be wrong by the same amount. If in radioactivity measurements we fail to take into account the background radiation which is always present, this will cause a systematic error in our readings. Another common cause of systematic error can be diagnosed by plotting a suitable graph: a line expected to show proportionality may not pass through the origin, for example.

Drift: This term speaks for itself: readings are not only not repeatable, but they move further and further in the same direction. Battery-powered instruments are prone to this, as their supply runs down, but there can be other causes: measurements of the length of a wire may drift because of changing temperature, for example. Sensitive electrical readings can sometimes drift because of temperature changes in components or at junctions between different conductors (causing thermoelectric e.m.f.s).

Loading effects: If we want to know the temperature of some water, we put a thermometer in it. But the thermometer takes some energy from the water, and thereby reduces the temperature *it* was *put there* to measure. In the same way, a voltmeter reduces the p.d. between the terminals of a battery to which it is applied, because *it* takes some current. In situations like this we say that the measuring instrument is *loading* the system to which we have applied it. (Load is a widely used term: the torch bulb is the load on the battery, the consumers' equipment is the load on a power station, and so on.) Loading does not always have to be taken into account, as it should be in the two examples above. The voltmeter built into a power supply is technically a load on the supply, but the reading it gives *is* the p.d. which that supply is providing, and as that is normally what we want to know, no correction is needed. Loading is relevant to more than measurement systems – see the article on 'Systems' in *Physics in engineering and technology.*

Validity: This is a term we apply to whole techniques rather than to instruments: is the apparatus measuring what we assume it is? To take a very obvious example, suppose we want to measure the rate of heating of some water by an immersion heater. If we put the thermometer high in the water it will show a rapid rise in temperature, but if we put it below the level of the heater its readings may change very slowly indeed. Neither set of readings is valid, because they are not values of the true average temperature of the water. Validity considerations can be much more subtle than this: does an ammeter read the correct value for an unsmoothed direct current? To answer that we have to think very hard about what we are going to use the reading for; in some cases the answer might be yes, in others it could well be no.

The effect of uncertainty upon conclusions

Once a set of readings has been taken, we have to assess what conclusions we can draw from them – *and* how uncertain the conclusions are. This involves a little calculation, and often makes use of graphs.

Graphs

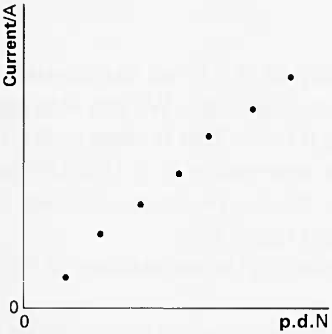


Figure 1

Two examples will help you to appreciate how uncertainty can be dealt with in terms of graphs.

1 If we are trying to find out whether two quantities are proportional (current and p.d. for some new component, perhaps), we generally draw a graph like figure 1.

Do these points seem to be indicating a straight line or not? If we hold the graph almost up to eye level and look along it from the origin, it looks like figure 2. This seems to show a very definite curvature away to the right.

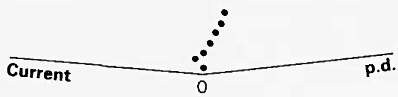


Figure 2

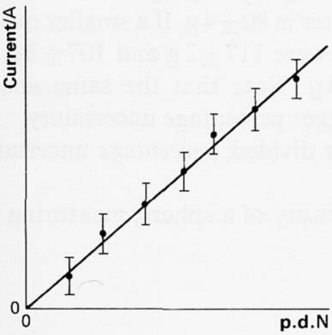


Figure 3

But suppose there were appreciable uncertainties in the readings plotted vertically. We can allow for this by plotting *error bars*, as in figure 3.

A straight line drawn through the origin and through all the error bars, now shows that a proportional relationship is *possible*. But 'possible' is the operative word. One inescapable fact in science is that no theory can ever be 'proved correct': we may believe very firmly in certain laws, but we have to recognize that one day a very careful experiment might disprove any one of them. Older text books often talked about 'verifying' laws. But no law can ever be positively verified: the most we can do is fail to contradict it – and to regard an experiment as an attempt to *disprove* something is often a very healthy attitude of mind.

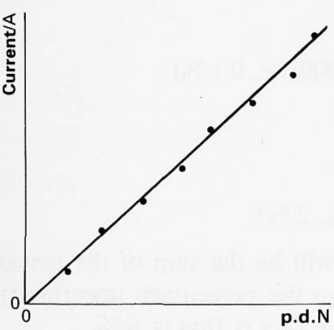


Figure 4

2 Suppose we are satisfied that a conductor obeys Ohm's Law (as closely as we will ever need), and we want to find its resistance. We could take a number of readings and calculate V/I for each, getting a series of different values and taking the average.

Yet this might not be the best thing to do. Plotting the results might give something like figure 4.

We can look at the lie of these points using a ruler (or better, a length of cotton) to 'average' much more intelligently. One point stands out as further from the general line than the rest. If we had simply taken the average V/I value, instead of drawing the graph and calculating its slope, this point would have been distorting the average, and therefore distorting our conclusion as to the most likely value for the resistance.

Finally, we can obtain from our graph a firm value for the highest and lowest possible values of the resistance, by drawing in the most extreme lines that can be fitted within the error bars (figure 5).

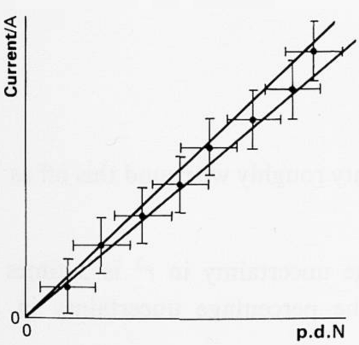


Figure 5

In these graphs we have shown variations and uncertainties which are quite large. Graphs of your own results will generally (though perhaps not always) be much more precise. It will be up to you to decide, in the light of the above ideas, how best to interpret them intelligently.

Calculation of uncertainty

If a reading is 8.6 with an uncertainty of ± 0.1, we can consider the figure 0.1 itself: it is called the *absolute uncertainty*. We can also express it as a fraction of the measured value: 0.1/8.6. This is close to 0.1/10, or 1 %, and we say that the *percentage uncertainty* is ± 1 %. (Note that since uncertainties are themselves a matter of estimation, we rarely write them to more than one significant figure.)

There are two simple rules for calculating the uncertainty in the final result of an experiment:

i Where quantities are added or subtracted, *absolute* uncertainties must be added.

Thus if a flask containing water weighs 187 ± 2 g and when empty weighs 107 ± 2 g, then the mass of water is 80 ± 4 g. If a smaller quantity of water was used, and the readings were 117 ± 2 g and 107 ± 2 g, then the mass of water would be 10 ± 4 g. Note that the same absolute uncertainty (± 4 g) is now a much bigger percentage uncertainty.

ii Where quantities are multiplied or divided, *percentage* uncertainties must be added.

For example, in calculating the density of a sphere, measuring mass and radius, we write

$$\rho = \frac{m}{\frac{4}{3}\pi r^3}.$$

Suppose

$m = 90.2 \pm 0.1$ g

$= 0.0902 \pm 0.000\,1$ kg (about 1 in 1000, *i.e.*, 0.1 %)

and

$r = 4.8 \pm 0.1$ cm

$= 0.048 \pm 0.001$ m (about 1 in 50, *i.e.*, 2 %)

The percentage uncertainty in ρ will be the sum of the percentage uncertainty in m (0.1 %), and *3 times* the percentage uncertainty in r (because the formula involves r^3, *i.e.*, $r \times r \times r$), that is, 6 %.

This amounts to 6.1 % in all, so we write

$$\rho = \frac{0.0902\ \text{kg}}{\frac{4}{3}\pi \times (0.048)^3\ \text{m}^3} \pm 6.1\ \%$$

$= 195\ \text{kg m}^{-3} \pm 6.1$ %

$= 195 \pm 11.9\ \text{kg m}^{-3}$ by calculator

Since we only know the uncertainty roughly we round this off as

$\rho = 190 \pm 10\ \text{kg m}^{-3}$

Note that just as the percentage uncertainty in r^3 is 3 times the percentage uncertainty in r, so the percentage uncertainty in $\sqrt{x}$ ($= x^{1/2}$) is *half* that in x, and so on.

ACKNOWLEDGEMENTS

One of the pleasantest aspects of the development of *Revised Nuffield Advanced Physics* has been the willing way in which so many people have contributed and become involved in the work. Above all, teachers have helped in many ways, and the very number who have done so makes it impossible to acknowledge the contribution of each individual. Many have offered suggestions at meetings or have written in with ideas for questions, demonstrations, and so on. We have tried to consider carefully all the suggestions put forward and, inevitably, it is impossible to give proper credit to the source or origin of every idea we have used. One who has made a particularly valuable contribution in this way is Colin Price. To him and the many others whose contributions go unacknowledged, we offer our sincere thanks.

Other teachers have helped by conducting trials of some of the more radically changed parts of the course, and of a major innovation – the 'Dynamic modelling system'. The trial schools are: Aylesbury Grammar School; Beechen Cliff School, Bath; Bexley-Erith Technical High School, Bexley; Bishop Hedley High School, Merthyr Tydfil; Cheltenham College; Esher College; Forest Hill School, London; Godolphin and Latymer School, London; The Grammar School, Batley; The Greenhill School, Tenby; Haverstock School, London; Heathland School, Hounslow; Henbury School, Bristol; Highfield School, Wolverhampton; Howell's School, Llandaff; King Edward VI College, Nuneaton; Kingsbridge School; Lady Margaret High School, Cardiff; Malvern College; Marlborough College; Netherhall School, Cambridge; North London Collegiate School; Northgate High School, Ipswich; Oulder Hill Community School, Rochdale; Richmond-upon-Thames College; Royal Grammar School, High Wycombe; Rugby School; Samuel Ward Upper School, Haverhill; and Sutton Manor High School.

We are grateful to the Inner London Education Authority for trying some of our material on electronics in their 1983 Summer School for sixth-form students at the North London Science Centre.

Mark Ellse has read and commented on much of the draft material, and has made particularly useful suggestions about the up-dating of some experiments and pieces of equipment.

Thanks are due to a group of teachers, convened by Bob Fairbrother, who met several times to discuss assessment. Their suggestions led to some changes in the structure of the examination.

Others, as well as teachers, have helped, of course. While he was working as a technician at the Centre for Science and Mathematics Education, Chelsea College, Phil Webb found time in a busy schedule to try out ideas for demonstrations and experiments, and to suggest ideas for new apparatus.

CLEAPSE School Science Service reviewed all the suggested experiments and demonstrations and made useful suggestions on the safety aspects of some of them.

Industry has helped too, and, among others, we are indebted to Rank Xerox, Amersham International P.L.C., and the CEGB for technical help and information.

Examination questions in the *Students' guide* are reprinted by permission of the Oxford and Cambridge Schools Examination Board. With one exception all are taken from Oxford and Cambridge Nuffield A-level Physics papers. The exception is one question taken from an Oxford and Cambridge O-level Nuffield Physics paper. Where guide lines for answers to examination questions are provided it must be understood that these are not the Examination Board's responsibility.

The Consultative Committee have, I believe, been asked to work harder and contribute more than is usually expected of such a group. As well as attending many meetings they have read and commented in detail on draft manuscripts – sometimes in a far from ideal state – and they have done all this most willingly.

It is a pleasure to acknowledge E. J. Wenham's help and sound advice. Much of what is written in these books has benefited from his knowledge and experience as teacher and author.

All of us who have contributed to these books owe a great debt of gratitude to Nina Konrad and her colleagues in the Publications office of the Nuffield–Chelsea Curriculum Trust for their thorough and painstaking work in preparing our manuscripts for the printers and our sometimes quite inadequate drawings for the artists.

Finally, I would like to express my sincere thanks to Paul Black and Jon Ogborn. Their help and support has been invaluable. During a period when both have been particularly busy, they have still found time to give advice both on general matters and on points of detail. They were, of course, the chief architects of the original Nuffield Advanced Physics course. Their willingness to be involved with what must at times have seemed like a severe distortion of their original plans, says much about their generosity of spirit.

John Harris

Unit A
MATERIALS AND MECHANICS

Roger Hackett
Christ's Hospital, Horsham

A

SUMMARY OF THE UNIT

SUMMARY OF THE UNIT

INTRODUCTION

This Unit is about the science of the materials upon which a technologically based society depends for its buildings, bridges, tunnels, lorries, fabrics, telecommunications equipment, tubes, rails, and so on. The application of the science is the province of the engineer who must design and construct large and small structures, choose the most appropriate materials for the job, calculate the forces which will exist within the structure when in use, and achieve the best balance between cost and function.

The scientist is responsible for investigating the properties of the materials used by the engineer, whether these are metals, woods, glasses, plastics, etc. This involves the measurements of the effects of applied forces, studies of the behaviour of the materials under widely varying conditions, consideration of the energy stored within the material when in use, all of which determine the suitability of the material for its purpose.

To understand the information obtained, scientists need a theoretical model for materials in general. Such a model, based upon experience in the laboratory and in the field, will allow them to predict how the material under study will behave under various conditions. It may also allow them to develop new materials to meet specific needs. Such materials are often composite, for example, concrete, glass fibre, plywood.

Using simple ideas from mechanics, the kinetic theory (or model) of gases is developed to account for many properties of real gases.

Some of the topics and ideas within the Unit will be developed further later in the course. For example, the nature of the force between atoms will be taken up in Unit E, 'Field and potential', the oscillations of mechanical systems will be examined in Unit D, 'Oscillations and waves', and the important theme of randomness will be used in a different context in Unit K, 'Energy and entropy'.

Section A1 THE BEHAVIOUR OF MATERIALS

Descriptive terms

QUESTION 4 We need to study how materials behave under the action of forces so that we can choose the most suitable for a particular job. What, for example, are the best properties for the material with which to make the springs of an easy chair or the cables of a suspension bridge? The behaviour of constructional materials under the action of forces is described by words to which very specific meanings are attached. For example, steel which is strong under steady tension and compression deforms elastically and is stiff with soft yielding near the point of fracture. Brief explanations of some of these terms follow.

Tension, compression, and shear

QUESTIONS 1, 2

The size of the force needed to deform a material by a given amount, or to break it, depends on how the force is applied. Pulling on both ends of a specimen causes *tension*; pushing on both ends causes *compression*; twisting both ends in opposite directions causes *shear*. Most of the examples in the course are concerned with tension.

Stress and strain

$$\text{Tensile strain} = \frac{\text{extension}}{\text{original length}}$$

$$\text{Tensile stress} = \frac{\text{applied force}}{\text{cross-sectional area}}$$

The size of a specimen must be taken into account when comparing the deformations produced by the applied forces. In the case of stretching under tension the ratio of the extension, x, to the original length, l, is called the *strain*.

The ratio of the tension in the specimen, F, to the cross-sectional area, A, is known as the *stress*.

A

Stiffness

A *stiff* material is one in which a large stress is required to produce a small strain. Stiff materials have high Young moduli.

Strength

EXPERIMENTS A3, A4, A5
Strengths of aluminium, glass, and paper

HOME EXPERIMENT AH1
Saved by a hair!

QUESTION 9

A material is *strong* if a large stress is required to break it. The *breaking stress* (ultimate tensile stress) is the stress needed to break the material. A material may be stiff but not strong, such as a biscuit; quite strong but not very stiff, such as nylon; both strong and stiff, such as steel. Some materials are strong in compression but weak in tension, such as brick and concrete.

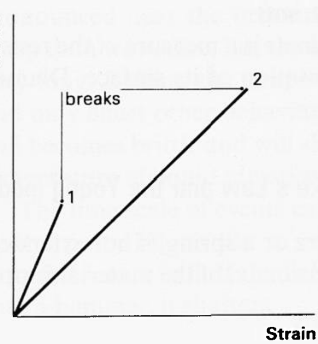


Figure A1
1 is twice as stiff as 2; 2 is twice as strong as 1.

Elastic; plastic

An *elastic* material returns to its original shape after the deforming forces are removed, with no loss of energy. Steel and many other metals are elastic for small strains (up to about one-tenth of one per cent). Materials which flow, slip, or slide internally long before they break are said to show *plastic* deformation. Plasticine is an obvious example, as are metals which can be hammered or pressed into new shapes.

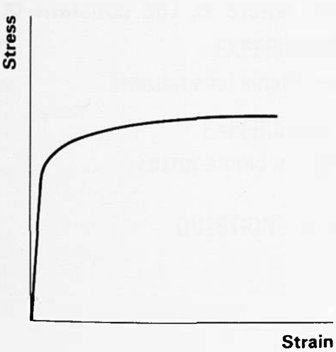


Figure A2
Stress–strain curve for a plastic material.

Tough

EXPERIMENT A2
Stretching rubber, nylon, polythene

A *tough* material will deform plastically before breaking. Examples include steel, which has a high breaking stress and nylon, which has a much lower breaking stress.

Brittle

EXPERIMENT A4
Breaking strength of glass fibre

Materials which do not deform plastically before breaking are *brittle*. They snap cleanly and the edges fit together after breaking. Glass, pottery, and concrete are brittle.

EXPERIMENT A7
Effect of cracks

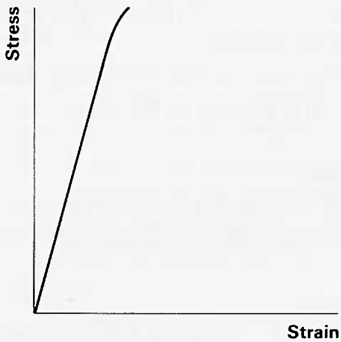


Figure A3
Stress–strain curve for a brittle material.

Ductile, malleable

EXPERIMENT A1
Stretching, bending, and breaking materials; force–extension relationship

Ductile materials can be drawn into wires and *malleable* materials can be hammered into new shapes. Both processes involve plastic deformation.

Hard, soft

QUESTION 3

Hardness is a measure of the resistance of the material to scratching and indentation of its surface. Diamond is the hardest substance found in nature.

Hooke's Law and the Young modulus

What are the units of k?
k is called the *spring* or *force constant*

A wire or a spring, if not extended too far, will obey Hooke's Law. The extension, x, of the material is proportional to the applied force, F.

$$F = kx$$

QUESTIONS 5 to 8

The Young modulus $= \dfrac{\text{tensile stress}}{\text{tensile strain}}$

What are the units of E?

Hooke's Law may be written: stress is proportional to strain, if the strain is not too large. Stress $= E \times$ strain, where E, the constant of proportionality, is called the *Young modulus*.

$$E = \text{stress/strain} = \frac{F/A}{x/l}$$

EXPERIMENT A6
Behaviour of springs

HOME EXPERIMENT AH2
An accurate newtonmeter

Since

$$k = F/x$$

$$k = EA/l$$

QUESTION 10

EXPERIMENT A8
The Young modulus for the material of a wire

QUESTION 9

READING
Mechanical testing of materials (page 23)

The Young modulus is important because it depends only on the material, not the size and shape of the specimen. It can be found from the slope of the linear (elastic) region of the stress–strain curve. For a typical metal wire the limit of proportionality is reached for a strain of 0.001, and the Young modulus may be 10^{11} N m^{-2}.

An engineer may also need to know the *yield strength*, the stress at which plastic deformation becomes important.

The treatment which a wire specimen has undergone before it is tested often affects its properties. For example, a wire which has been flexed a number of times, or squashed at one point, will behave differently from a new, undamaged one. The stress–strain curve will be different and the wire will fail at a lower stress. Most wires found in the laboratory have been made by drawing through a circular die and have thus been subject to considerable stress. This partly explains why the stress–strain curves for new short rod specimens tested in automatic extensometers and reproduced in many textbooks exhibit features not observable in simple laboratory experiments with cold drawn wires. Automatic extensometers are hydraulic machines which can sense any reduction in stress in the specimen although the strain is still increasing. Such an effect cannot be observed with simple equipment.

A

Time and temperature effects

A material under a continuous stress which is not large enough to break it, may gradually extend more and more. This *creep* is shown by rubber bands, and by lead and materials such as pitch and tarmac. Metal wires creep if stressed beyond their yield point, and the effect becomes more pronounced near the breaking stress. Probably more materials show creep than we realize, but the time needed for an observable extension is very long. Raising the temperature usually increases the rate of creep and may affect other behaviour of the material. For example, a rubber ball becomes brittle and will shatter if dropped after being cooled to the temperature of liquid nitrogen.

EXPERIMENT A5
Strength of paper

The time scale of events can also alter the behaviour. Silicone putty ('potty putty') flows like a viscous liquid if left alone. It can also be moulded into a ball. If the ball is dropped, it bounces elastically. If hit with a hammer, it shatters.

Elastic strain energy

EXPERIMENT A9
Translational kinetic energy

EXPERIMENT A10
Energy stored in a spring

QUESTIONS 11 to 16

Energy is transformed when a specimen is stretched. Although the stretching force is not constant, the work required to produce a given extension is given by the area under the force–extension graph. For a material obeying Hooke's Law and not stretched beyond its elastic limit, the energy stored in the strained specimen, W, can be found from the area of the triangle under the force–extension curve (figure A4):

area = (average force) × (extension)

$W = \frac{1}{2}Fx = \frac{1}{2}kx^2$

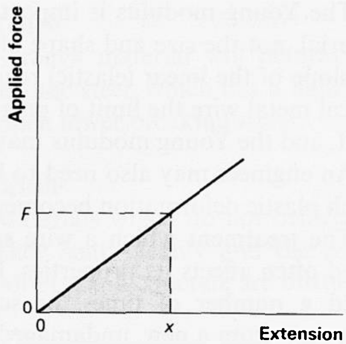


Figure A4

By expressing the applied force and extension in terms of tensile stress and strain, we can show that the elastic strain energy stored per unit volume $=\frac{1}{2}$(stress) × (strain).

QUESTION 14

If the stretch is elastic (that is, if the specimen returns to its original shape when the applied force is removed) all the stored energy is recoverable, for example as kinetic energy.

QUESTION 17

For a specimen not obeying Hooke's Law (figure A5), or one stretched beyond its elastic limit, the area under the force–extension graph is still a measure of the energy transformed, but $W=\frac{1}{2}kx^2$ cannot be used. When such a sample is released, the area between the loading (upper) curve and the unloading (lower) curve represents the energy transformed in deforming the specimen and so heating it. The closed curve shown for rubber is an example of elastic hysteresis and is important in the behaviour of tyres.

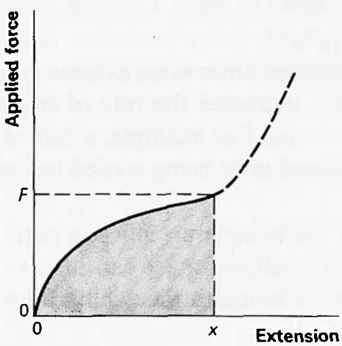


Figure A5

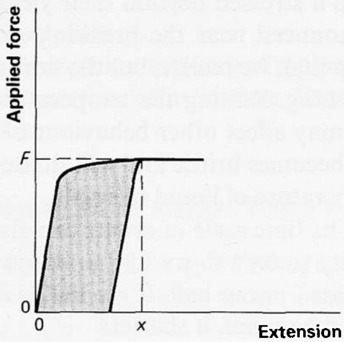


Figure A6
Force–extension curve for copper.

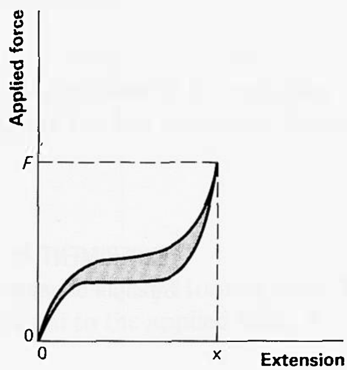


Figure A7
Force–extension curve for rubber.

EXPERIMENT A11
Changing elastic strain energy into gravitational P.E. or translational K.E.

Gravitational P.E. $= mgh$

Translational K.E. $= \frac{1}{2}mv^2$

DEMONSTRATION A12
Energy absorbed in deformation

Experimental attempts to check the expression for elastic strain energy assume that the Law of Conservation of Energy applies and arrange to convert the elastic strain energy into another measurable form. Typically this is the gravitational potential energy of a mass, or the kinetic energy of a vehicle. The success of such experiments depends on how completely the stored elastic energy is transformed into one single measurable form.

The transformation from kinetic to strain energy has to be considered in the design of safety belts and in the choice of materials for items such as climbing ropes, crash barriers, and car chassis.

Section A2 THE STRUCTURE OF SOLID MATERIALS

Atoms and molecules

All matter is made up of particles consisting of single atoms, molecules, or ions. Knowledge of their sizes and how they are arranged in various materials leads to a better understanding of why materials behave differently and exhibit different properties. The arrangement of atoms in a metal such as copper is quite simple. Such substances as rubber, polythene, wood, and concrete are rather complicated chemically, and have correspondingly complex structures.

READING
Models (page 31)
Theories – true or not? (page 32)

As well as a physical model of the structure of materials, physicists need a mathematical model for the dependence of the forces between atoms or molecules and their separation.

QUESTION 18

EXPERIMENT A13
Optical analogue for X-ray diffraction

Unit J, 'Electromagnetic waves'

The upper limit to the size of a molecule was estimated by Lord Rayleigh in 1899 by pouring a thin layer of oil onto water. He argued that the layer of oil could not be less than one molecule thick. Later (in 1912), von Laue passed a beam of X-rays through a crystal and observed different patterns of spots on a photographic plate depending on the crystal used. Sir Lawrence Bragg, using an X-ray spectrometer his father had invented, developed this technique so that it was possible to relate the systems of spots and rings to the arrangement and spacing of the atoms in the crystal. This same method has been used and refined to such an extent that the incredibly complex structures of such very large organic molecules as vitamin B12 and DNA have been unravelled. Several researchers have won the Nobel prize for this work.

READING
Looking at the structure of materials (page 24)

Atom about 10^{-10} m in diameter

Modern developments in electron and field-ion microscopes give more direct evidence for the arrangement and spacing of atoms in crystals. The photographs shown were taken with a 600 kV electron microscope at Cambridge.

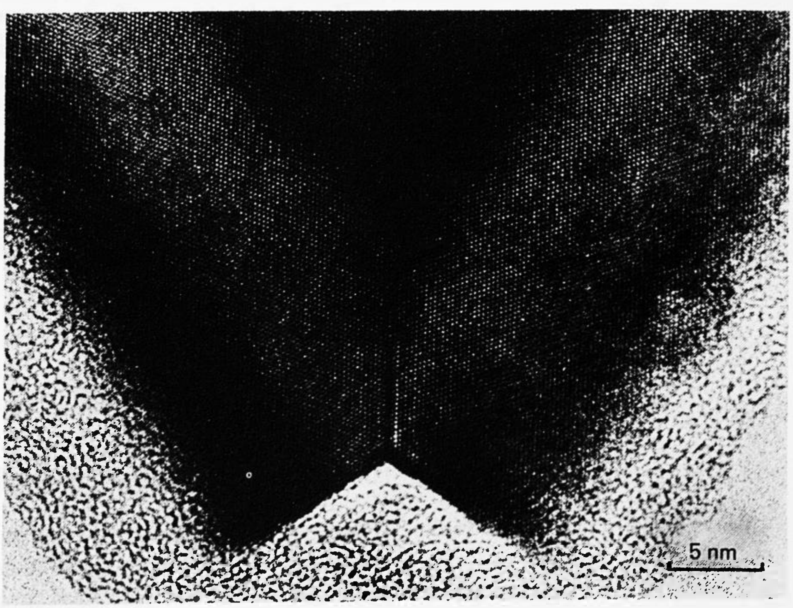


Figure A8
1 nm (nanometre) = 10^{-9} m
(a) A small particle of magnesium oxide. It shows a very clear twin boundary. The atomic arrangement on one side of the boundary is the mirror image of the arrangement on the other.
NEWCOMB, S. B., SMITH, DAVID J., and *STOBBS, W. M.* J. Microsc. **130** *p. 137, 1983.*

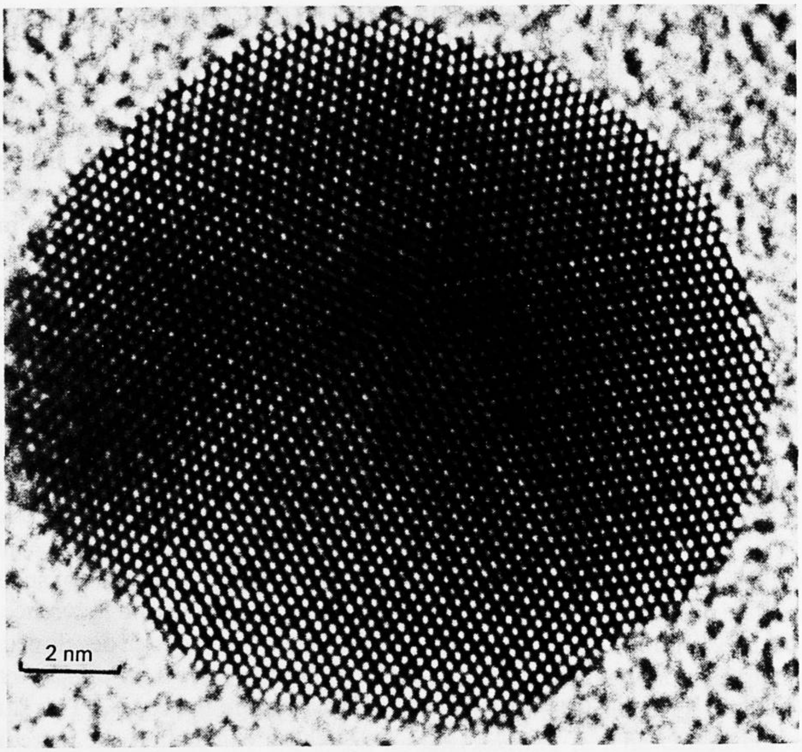


Figure A8
(b) A small particle of gold. The rows of atoms are viewed end-on with each row showing up as a white spot. Note the hexagonal arrangement of atoms and five twin boundaries.
MARKS, L. D. and *SMITH, DAVID J.*
J. Microsc. **130** *page 249*, 1983.

The mole and molar mass

'Mole' means heap, or pile

QUESTIONS 20, 24

The fact that the volumes of combining gases are always in simple ratio led Avogadro to suggest, early in the nineteenth century, that equal volumes of gases (at the same temperature and pressure) contain equal numbers of particles.

The Avogadro constant, L

It is useful to specify an amount of a substance that contains a specific number of individual particles. The appropriate SI unit is the mole: the amount of substance which contains as many elementary entities as there are atoms in 0.012 kg of carbon-12. One mole contains 6.02×10^{23} particles, so it is unusual to apply the idea to anything not of atomic or molecular size.

QUESTIONS 20 to 22

The molar mass of a substance is the mass of one mole of particles, and it is essential to say what the particles are – atoms, molecules, ... The molar mass of hydrogen atoms (H) is 0.001 kg mol^{-1}, but the molar mass of hydrogen molecules (H_2) is 0.002 kg mol^{-1}. Copper atoms have a molar mass of 0.0636 kg mol^{-1}.

The mass and size of an individual atom can be estimated by assuming that the atoms in a solid are in contact.

Forces between atoms and molecules

Ionic: NaCl
Covalent: H_2 CH_4
Metallic: metals

Atoms are held together in molecules by electrical forces. The different kinds of bonding which chemists call ionic, covalent, or metallic are all electrical. There are electrical forces between molecules too, and the forces depend on how far apart the molecules are. In a gas the average distance between two molecules is so large (about 10 molecular diameters) that the force between them is negligible.

The behaviour of solid materials under tension suggests that powerful attractive forces exist between molecules which are close together. Similarly, their behaviour under compression suggests that there are also repulsive forces which increase very rapidly with diminishing separation. At the equilibrium separation, r_0, these two forces are equal and opposite (zero resultant force).

QUESTIONS 25, 26

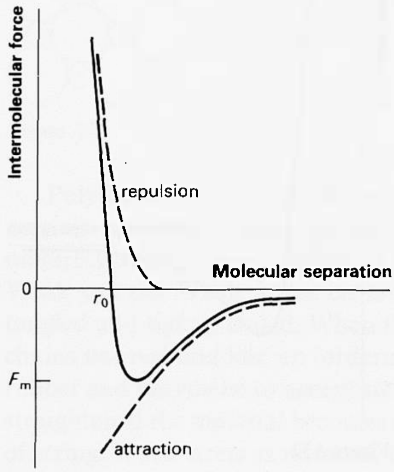


Figure A9

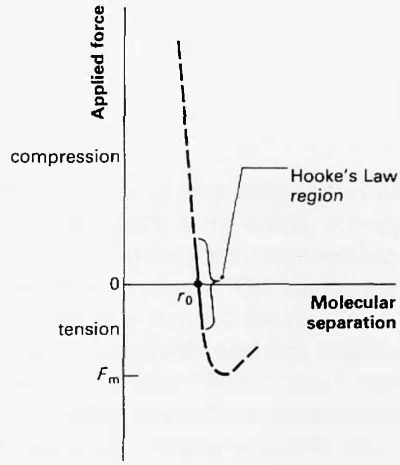


Figure A10

Hooke's Law
$F = k\Delta r$

The gradient of the force–distance curve indicates the stiffness of the solid, and if the curve is linear close to r_0, then the substance obeys Hooke's Law. Brittle fracture will occur when the force applied to the solid is greater than the maximum molecular attraction, F_m.

The Young modulus and the interatomic force constant

$E = \frac{\text{tensile stress}}{\text{tensile strain}}$

QUESTIONS 28, 29, 30

The origin of the elastic behaviour of a solid being stretched or compressed, and so of Hooke's Law, lies at atomic level. Imagine two sheets of atoms, equilibrium distance, r_0, apart, being pulled elastically a distance Δr, by a force F. The atoms can be pictured as being held together by small springs of force constant k. This interatomic force constant is related to the Young modulus, E, by the equation:

$k = Er_0$

For steel $E \approx 2 \times 10^{11}\,\mathrm{N\,m^{-2}}$

and $\quad r_0 \approx 3 \times 10^{-10}\,\mathrm{m}$,

so $\quad k \approx 60\,\mathrm{N\,m^{-1}}$.

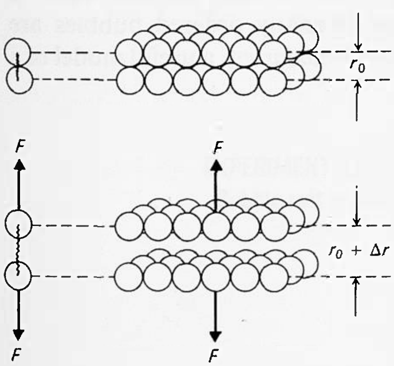


Figure A11

Intermolecular energies

DEMONSTRATION A15
Intermolecular force–distance model using air track

Two molecules have zero potential energy when an infinite distance apart. As they move together they lose potential energy because of the attractive force between them: the potential energy becomes negative. At the equilibrium separation, r_0, the energy is a minimum. Work must be done to push them any closer together. The deeper this 'potential well', the greater the binding energy, the energy needed to separate the molecules completely from the equilibrium position.

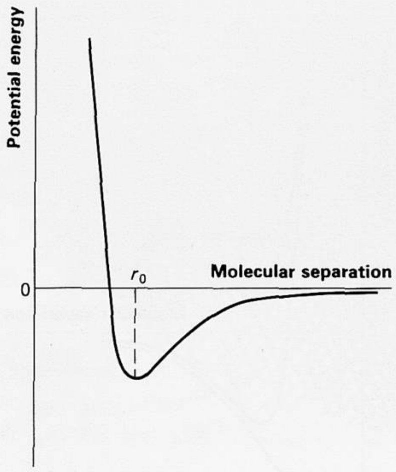


Figure A12

QUESTION 27

When a material is heated, its molecules gain energy: in a gas the molecules move faster; in a solid they depart from their equilibrium positions. The solid will sublime or the liquid vaporize when the kinetic energy of molecules is equal to the binding energy. The energy needed to sublime a mole of the solid or to vaporize a mole of the liquid (the molar latent heat) can be measured. From this measurement the binding energy per molecule can be estimated for solids and for liquids.

Structure of solids

EXPERIMENT A16b
Bubble raft model

Atoms linked by metallic bonds form simple structures, since this bond has equal attractions in all directions. A model of a metal structure in two dimensions can be made using a raft of soap bubbles. Each is surrounded by six neighbours. Areas of neatly ordered bubbles are formed, divided by discontinuities (*grain boundaries*), a useful model of a *polycrystalline solid.*

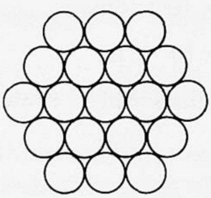


Figure A13

Many metal crystals (copper, aluminium, and magnesium, for example) are made up of layers of hexagonally arranged atoms packed together as closely as possible. Some metals (including sodium, and iron at temperatures below 900 °C) form crystals in which the atoms are in a slightly more open arrangement.

QUESTION A23

Sodium chloride is an example of an ionic crystal. The small sodium ions, Na^+, fit into the holes in the packing of the larger chloride ions, Cl^-.

DEMONSTRATION A14
How atoms are arranged in solids

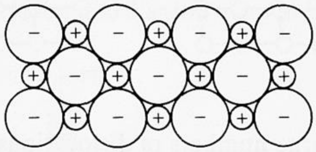


Figure A14

EXPERIMENTS A2
Stretching rubber, nylon, polythene

Polythene, rubber, and nylon are examples of very long chains of organic molecules called *polymers*. Within each long chain, strong unidirectional covalent bonds hold carbon and hydrogen atoms together. Weak van der Waals forces cross-link between chains. The chains are tangled and tightly coiled. When the material is stressed the molecular chains unravel and line up (ordering of the structure), and this enables rubber and polythene to accept strains of more than 100 per cent. Once straightened the material becomes much stiffer, like pulling out a tangle of string. If the stress is released, the molecular chains return to their original tangled and coiled state.

EXPERIMENT A16a
Splitting stretched rubber

QUESTIONS 31 to 33

Structures in which the same regular arrangement covers very many atoms or ions (long range order) are called *crystalline*. Completely irregular structures or those with only very short range order are called *glassy* or *amorphous*. In glass, the disordered liquid structure is maintained into the solid state. Polymeric solids, such as polythene, rubber, hair, and wool, can exhibit both amorphous and crystalline properties depending on temperature and method of formation. Crystalline substances have precise melting temperatures, glasses do not.

Metals, unlike rubber or glass, can be hammered flat or drawn through a die to make wires. Metallic bonds enable layers of atoms to *slip* over each other rather than suffer brittle fracture like the disordered but strongly bonded glasses (figure A15).

The presence of dislocations can make slip easier than it would be in a perfect structure.

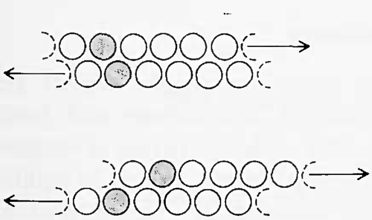


Figure A15

Dislocations

EXPERIMENT A16b
Bubble raft model

A dislocation is a single defect in the otherwise perfect and regular arrangement of atoms in part of a crystal. There are several kinds. One of the simplest occurs where a row of atoms stops and meets two rows instead of continuing on as it would in a perfectly regular arrangement.

The presence of a few dislocations can make a material soft or plastic, because the dislocations can run through the crystal causing slip. *Creep* is an example of the slow movement of dislocations through the crystal. The dislocations move as far as the grain boundaries before stopping.

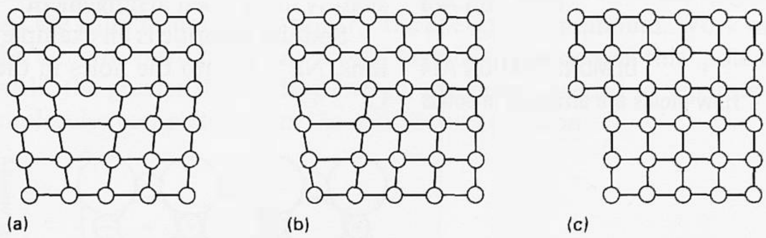


Figure A16

QUESTIONS 34 to 36

Large numbers of dislocations together reduce the ability of atoms to slip over each other, making the material stronger. *Work hardening* increases the number of dislocations through hammering, stretching, or bending, etc. In time, the dislocations can vanish again, especially if the material is kept hot, because dislocations of opposite types may come near each other and allow the atoms to 'snap back' into a regular arrangement, or they may travel to the edge of the crystal leaving only a step on the surface. This process is called *annealing*.

EXPERIMENT A16c
Heat treatment of steel

Introducing a certain number of foreign atoms into the material (*alloying*) can have the same effect as work hardening in reducing slip in a polycrystalline material, giving it greater strength. Heat treatment of the material can alter the arrangement of the foreign atoms in the material completely changing the properties of the alloy.

The presence of defects, such as dislocations, extra foreign atoms, or simply holes in the crystal pattern, means that the strength of real materials is usually much less than predicted for large perfect crystals.

Section A3 STATICS, STRUCTURES, AND COMPOSITE MATERIALS

Statics: structures and objects in equilibrium

Static: 'standing, at rest'

Mechanics deals with the effect of forces on simple objects and complicated structures. Part of it, dynamics, is concerned with forces that cause acceleration (change in velocity) or change in rate of rotation. Another part, statics, is about forces in equilibrium. Forces in equilibrium don't cause change in rotation or acceleration – this is Newton's First Law. But as seen in Sections A1 and A2, they do deform and may break an object. Statics allows engineers to calculate the stresses at critical places in a complex structure such as a building or a bridge.

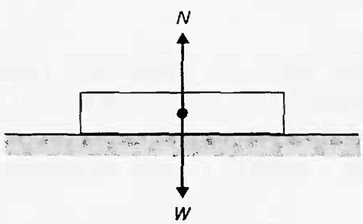


Figure A17

Contact forces: the 'normal' force, and friction

Typically statics is concerned with gravitational force (the weight of a body), forces caused by deformation (tension, compression), and forces due to friction. When a book rests on a table, the two forces acting on it are in equilibrium: the upward force of the table just balances the weight of the book. This upward force is called the 'normal' force, because it is perpendicular to the surface of the table. It is due to the compression of the table under the weight of the book – the molecules are slightly closer together, the repulsive force between them is increased.

A mass suspended from a spring will be in equilibrium if the upward force on it due to the tension of the spring balances its weight. The tension is caused by the extension of the spring – its atoms have been pulled slightly further apart than in the unstressed spring, and the attractive force between them is increased. An object at rest on a slope is in equilibrium because the forces acting on it – its weight, the normal force, and friction – are in balance.

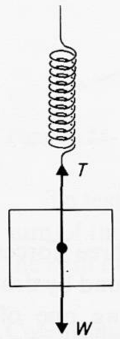


Figure A18

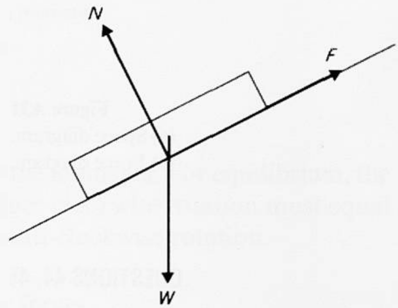


Figure A19

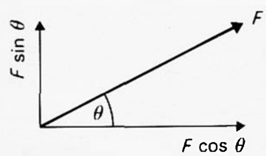


Figure A20

The components of a force

Force is a vector quantity, and any force can be resolved into two components. The vector sum of the two components is, of course, equal to the original force. If the two components are at right angles to each other, then,

$$F_x = F\cos\theta \qquad F_y = F\sin\theta$$

and

$$F^2 = F_x^{\,2} + F_y^{\,2}$$

QUESTIONS 37, 38, 42

$\Sigma F = 0 \Rightarrow \Sigma F_x = 0$ and $\Sigma F_y = 0$

Each of the forces acting on the body can be resolved in this way. If the sum of all the F_x components is zero there is no force tending to accelerate the body in the x direction, and similarly for the sum of the F_y components. For equilibrium both sums must be zero.

Addition of forces: triangle and polygon of forces

EXPERIMENT A17
Forces on systems in equilibrium

The resultant effect of several forces acting through a point is found by adding them, taking account of both magnitude and direction. Each force can be represented by a line whose length and direction represent the magnitude and direction of the force. The lines are drawn head to tail. Suppose there are three forces and these lines form a closed triangle: then their resultant is zero and the forces are in equilibrium (figure A21). If the triangle does not close, the set of forces does have a resultant and the body will accelerate.

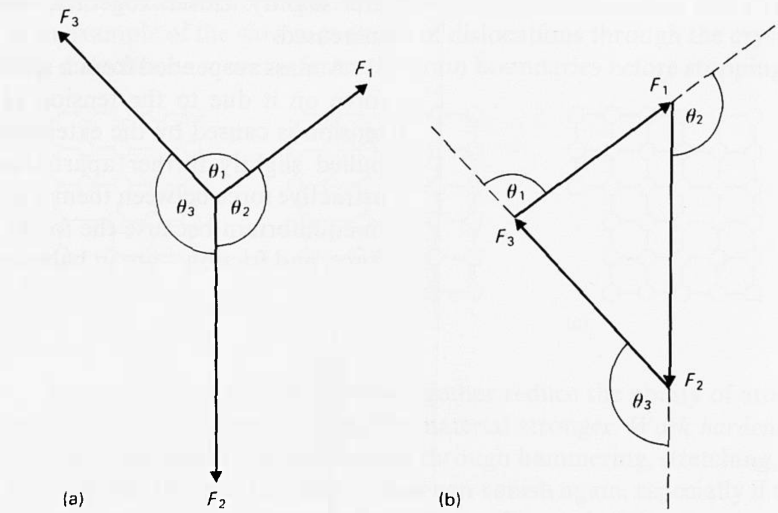


Figure A21
(a) Space diagram.
(b) Force diagram.

QUESTIONS 44, 45

With more than three forces the same technique applies: the resultant force can be found by drawing a polygon of forces, each side of the polygon representing one of the forces. The resultant force is represented by the line joining the first to the last point. If the polygon is closed, then the resultant force is zero.

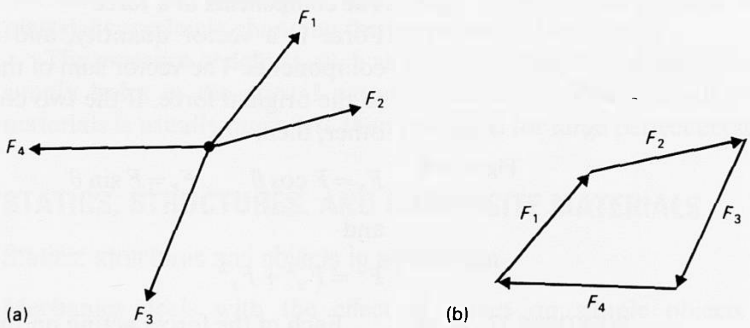


Figure A22
(a) Space diagram.
(b) Force diagram.

Moments and couples

The *moment* or turning effect of a force about a given point is the product of the force and the perpendicular distance from the point to the line of action of the force.

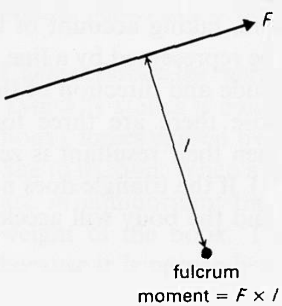


Figure A23

QUESTIONS 39, 40, 41, 43

EXPERIMENT A18
Loaded bridge

A *couple* consists of two forces, equal in magnitude but opposite in direction, which do not pass through a point. The effect of a couple on a body is to change its rate of rotation: a couple does not cause any linear acceleration.

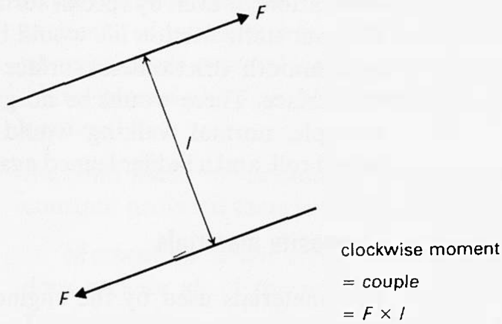


Figure A24

EXPERIMENT A19
'Weighing' a retort stand
$\Sigma(\text{moments}) = 0$

To test for equilibrium we add all the moments. For equilibrium, the sum of the moments tending to produce clockwise rotation must equal the sum of those tending to produce anti-clockwise rotation.

Conditions for equilibrium of coplanar forces
Both conditions discussed above are necessary for equilibrium:
i the sum of the resolved components of all the forces in any two perpendicular directions is zero, and
ii the resultant moment about any point in the plane of the forces is zero.

If condition *i* is true the body will not accelerate; if condition *ii* is true its rate of rotation (if any) will not change. If all the forces pass through one point (concurrent forces) then condition *i* is sufficient. Condition *ii* is also required for non-concurrent forces.

EXPERIMENT A20
Forces in a roof truss

These are the rules used to calculate the forces which exist within any rigid structure, such as bridges, towers, cranes, electricity pylons, and so on.

Static friction
When two surfaces in contact are at rest, the frictional force between them, parallel to the contact plane, opposes their relative motion and can have any value up to a limiting value. The ratio of the maximum frictional force, F, just as motion begins, to the normal force, N, is called the coefficient of static friction, μ.

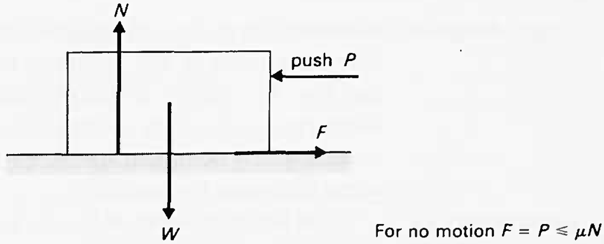


Figure A25

EXPERIMENT A17c
Coefficient of friction

Friction plays an important role in all mechanical situations, some beneficial, some inconvenient. Dynamic (moving) friction usually causes translational or rotational energy to be transformed into thermal energy. Friction is reduced by ball-, roller-, or fluid-bearings, by lubrication, or even by special surface coatings such as PTFE ('Teflon'). Without static friction life would be intolerable, since the contact force at a 'smooth' (frictionless) surface is normal, that is, at right angles to the surface. There would be no grip between surfaces in contact. For example, normal walking would be impossible, no ordinary wheel would roll, and a ladder leaned against a wall would slide to the ground.

Composite materials

Few materials used by the engineer are pure substances. Many pure metals, for instance, are soft and relatively weak.

QUESTIONS 46 to 49

HOME EXPERIMENT AH3
The jelly column

HOME EXPERIMENT AH4
Cement

READING
Materials used in architecture (page 33)

See Section A2 page 12

Composites are combinations of materials where each retains its own properties but the combination leads to a wider range of applications. For example, ordinary glass fibres are strong, but brittle when scratched. Encasing the fibres in a resin produces a tough material, glass fibre, which resists cracks. Glass fibres are flexible, but the material glass fibre is stiff. Carbon fibres in a polymer resin produce a material which is lighter and stronger than steel. Concrete is strong in compression but weak in tension. Through the use of steel rods, a stronger more useful composite material, reinforced concrete, is made.

Alloys are a mixture of a pure metal with other elements. For example, steel is formed by adding a small quantity of carbon to iron. Different amounts of carbon give the alloy different properties. Special steels for specific applications may contain elements such as chromium, tungsten, and nickel. The engine blocks of some modern motor car engines are made of an aluminium alloy which is as strong as steel, but much lighter. Strong modern plastics have also replaced metals in some applications, reducing both cost and mass.

In any branch of technology, progress depends on the availability of the right material for the job. The development and use of new substances and the application of existing materials through new machining techniques (for example, superplastic moulding of metals such as titanium) together make possible continuing advances.

Section A4 MOMENTUM AND THE SIMPLE KINETIC THEORY OF GASES

Newton's Laws of Motion, momentum, and impulse

Newton 1

Newton's First Law of Motion states that if no external resultant force acts on a body it will continue in its present state of rest or uniform motion. To change a body's state of motion, that is, to cause it to accelerate, a resultant external force must act on it. Newton's First Law is difficult to demonstrate because, in practice, there is nearly always some frictional force acting.

Linear momentum
$p = mv$

The *linear momentum, p,* of a body of mass m moving with velocity v is mv. Velocity, v, is a vector quantity, and so therefore is momentum.

$\Sigma p = \text{constant}$
$\Sigma \Delta p = 0$

Momentum is a useful and important quantity because it is a conserved quantity – it does not change. If no net force acts on a single body, then since its velocity does not change, neither does its momentum. For an isolated system of interacting bodies (for example the molecules in a jar of gas) the total momentum remains constant, though there may be an exchange of momentum between individual bodies. Isolated means that no unbalanced external forces act on the system.

In general the *Law of Conservation of Linear Momentum* can be written:

EXPERIMENT A22
Collisions on an air track

the total linear momentum of a system of interacting bodies remains constant provided there is no net external force.

A

Momentum is not conserved unless the system being considered does include all of the interacting bodies. For example, a swinging pendulum does not appear to conserve momentum, nor does a car accelerating. In both these cases the Earth is one of the interacting bodies and its motion must also be considered when applying the Law.

QUESTIONS 51, 53

If no resultant external force acts on the centre of mass of the system, then the vector sum of the momenta of all the constituent parts of the system relative to the centre of mass must be zero.

Newton 2

EXPERIMENT A21
Momentum change and impulse

Newton's Second Law describes the effect of an external resultant force on a body. A force, F, causes the body's momentum to change at a rate given by $F = \Delta p/\Delta t$. Or, in words:

QUESTION 50

the resultant force on a body is equal to the rate of change of linear momentum.

Impulse $= F\Delta t$

The product $F\Delta t$ is called the *impulse* of a force, and an alternative way of writing Newton's Second Law as $F\Delta t = \Delta p$ expresses the fact that

$F\Delta t = \Delta(mv)$

impulse = change of momentum.

The change in momentum of any body acted upon by a variable force can be found from the area under the force–time graph.

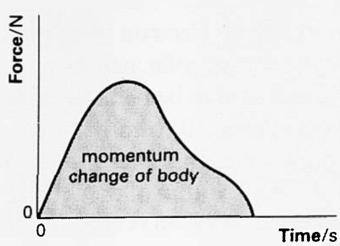


Figure A26

QUESTION 52

As long as the mass of the body does not change

$$\Delta p = \Delta(mv) = m\Delta v$$

and so

$$F = m\frac{\Delta v}{\Delta t} = ma$$

$F = ma$

force = mass × acceleration

Newton 3

Newton's Third Law of Motion is concerned with the forces between two interacting bodies. Forces always occur in pairs, one acting on each of the bodies: the forces have equal magnitude but are in opposite directions. So, for example, when two bodies collide they exert equal and opposite forces on each other, for the same time.

QUESTION 54

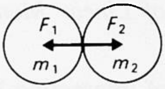


Figure A27

The Law of Conservation of Momentum follows from Newton's Third Law of Motion. Consider two bodies of masses m_1 and m_2 interacting for a time Δt. If the force on body 1 from body 2 is F_1, and the force on body 2 from body 1 is F_2, then $F_1 = -F_2$.

So the total impulse, $F_1\Delta t + F_2\Delta t = 0$.

And from the impulse–momentum change relationship $\Delta p_1 + \Delta p_2 = 0$.

The vector sum of the momenta of the two bodies interacting with each other is constant as the changes in momenta add to zero.

Elastic and inelastic collisions

Unit F, 'Radioactivity and the nuclear atom'

Evidence for the nuclear model of the atom, for the nature and mass of atomic particles, and explanations of the behaviour of matter described on an atomic scale come from the study of collisions.

EXPERIMENT A23
Newton's cradle

Collisions in which the total kinetic energy of the bodies before and after the collision is the same, are called *elastic collisions.* An electron can 'bounce off' a gas atom elastically exchanging little kinetic energy with the relatively massive atom. Alpha particles making elastic collisions with helium nuclei in a cloud chamber can transfer all of their energy to the helium nucleus if the collision is a head-on one. If it is oblique, then the particles will move apart at right angles, showing that they have equal mass. The mass of the neutron was determined by Chadwick (in 1932) by observing the elastic recoil of different nuclei making visible tracks in a cloud chamber.

EXPERIMENT A25
Collisions in two dimensions

QUESTIONS 55 to 59

Unit F, 'Radioactivity and the nuclear atom'

Situations where some of the kinetic energy is transformed to other forms of energy, such as internal energy (for example, random molecular motion), are called *inelastic collisions.* Two vehicles on an air track colliding and moving apart may interact inelastically. When an electron makes an ionizing collision with a gas atom some kinetic energy is lost in removing an electron from the atom. If the objects stick together, for example, an air rifle pellet fired into a lump of Plasticine, then the collision is said to be perfectly inelastic, but the total kinetic energy does not necessarily fall to zero.

EXPERIMENT A24
Speed of air rifle pellet

In all collisions where there are no resultant external forces acting the total momentum of the interacting bodies is conserved, regardless of whether the collision is elastic or inelastic.

The simple kinetic theory of gases

The ideal gas equation

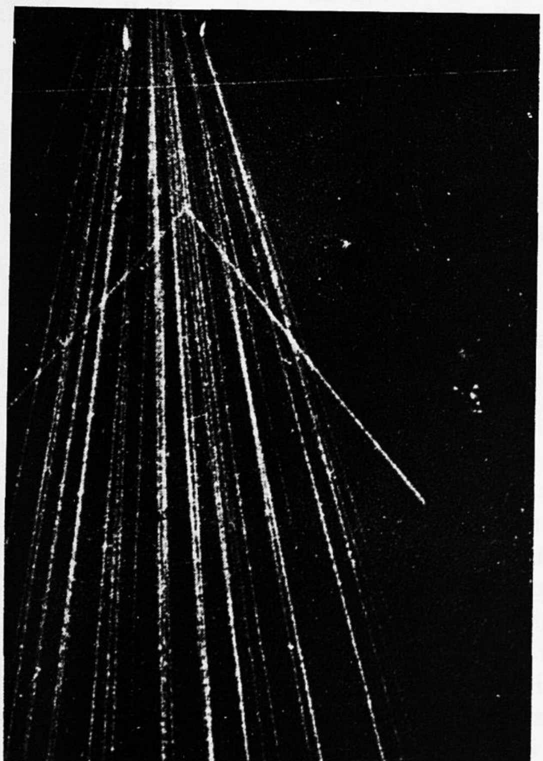
On a *macroscopic* scale, an *ideal gas* exactly obeys the relationship

$$pV = nRT$$

$R = 8.31\,\mathrm{J\,mol^{-1}\,K^{-1}}$

n is the number of moles of gas molecules present, and R is a universal constant called the *molar gas constant.*

(a)



(b)

(c)

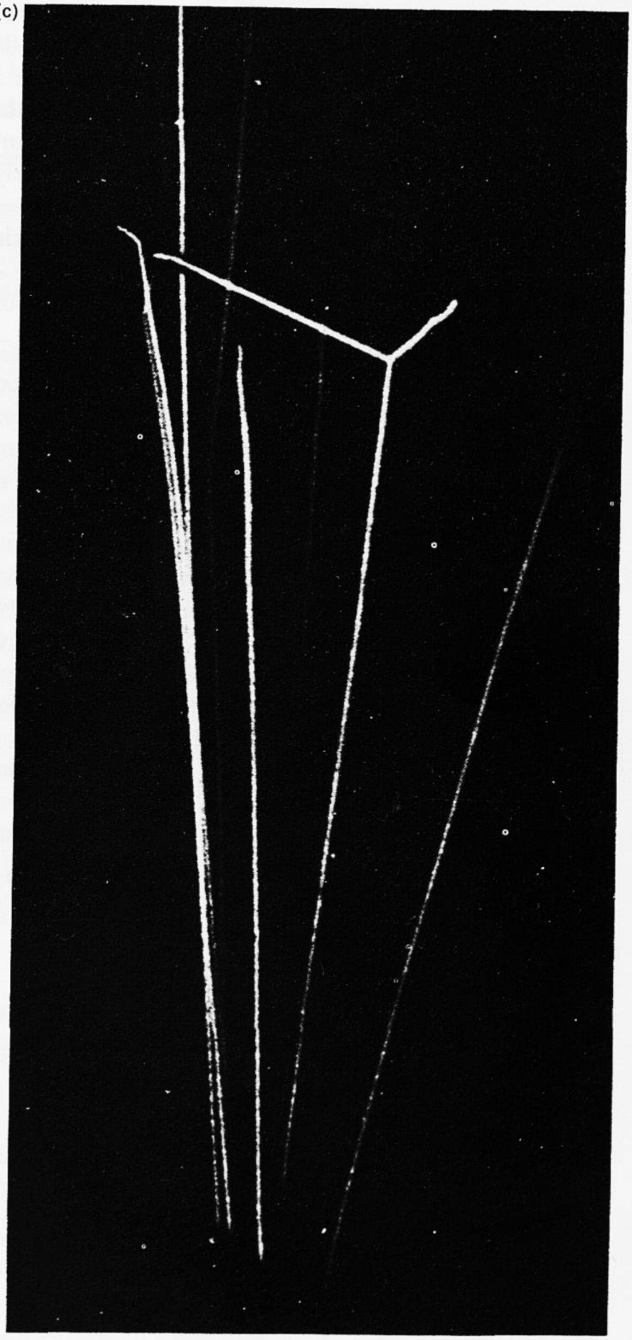


Figure A28
(a) Alpha particle tracks in wet hydrogen. One collided with a hydrogen nucleus, which recoiled forward and upward, making a thin track.
BLACKETT, P. M. S. Proc. Roy. Soc. *A. Vol. 107, Pl. 6(1)*, 1925.
(b) Collision of alpha particle with helium.
BLACKETT, P. M. S. Proc Roy. Soc. *A. Vol. 107, Pl. 6(3)*, 1925.
(c) Collision of an alpha particle with nitrogen.
BLACKETT, P. M. S.

QUESTIONS 60, 61

V_m is molar volume

Such a gas would obey Boyle's Law (pV = constant at constant temperature), and the Pressure Law ($p \propto T$, if volume is held constant) exactly. For one mole of ideal gas, $pV_m = RT$. This equation defines temperature on the ideal gas scale.

The behaviour of a real gas at low pressures and ordinary temperatures is very nearly ideal.

Assumptions of kinetic theory

On a *microscopic* scale we have a model for an ideal gas which embodies the following assumptions.

'Kinetic' means moving

i The ideal gas is made up of very large numbers of identical monatomic molecules. They are in constant random motion colliding by chance with one another and with the walls of the container.
ii These collisions are (at least on average) elastic, so that the total kinetic energy of the molecules remains constant; and the centre of mass of the gas is at rest.
iii The volume of the gas molecules themselves is negligible compared with the volume of the container.
iv The forces between molecules are negligible except during collisions. Collisions occupy a negligible time in comparison to the time between collisions; the molecules move with uniform velocity between collisions (gravitational effects are ignored).

QUESTION 64

The pressure in an ideal gas

QUESTIONS 62, 63

Applying Newtonian mechanics to the very large number of molecular collisions with the walls of the container per second enables the product pV for a quantity of gas to be related to the mean square speed, $\overline{c^2}$, of its molecules.

$$pV = \tfrac{1}{3}Nm\overline{c^2}$$

where there are N molecules each of mass m.

Also, since density $\rho = Nm/V$

$$p = \tfrac{1}{3}\rho\overline{c^2}$$

The root mean square (r.m.s.) speed of air molecules $\sqrt{(\overline{c^2})}$ at room temperature and pressure is about 500 m s^{-1}. The speeds of the molecules are very varied and are distributed as suggested in figure A29.

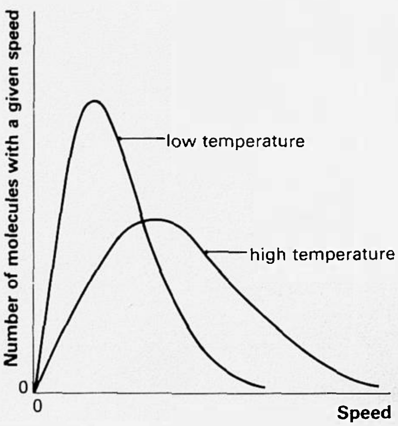


Figure A29

The kinetic interpretation of temperature

M is molar mass

The total kinetic energy of the molecules in one mole of gas is $\tfrac{1}{2}M\overline{c^2}$. Using the above equation for pressure and the ideal gas equation, the total kinetic energy per mole $= \tfrac{3}{2}RT$.

A monatomic ideal gas can only store energy by its translational motion. (Diatomic gas molecules can store energy by rotating and vibrating too.) For an ideal gas the total kinetic energy is the internal energy of the gas, U.

The molar heat capacity of the ideal gas (the energy required to raise the temperature of one mole of the gas by one kelvin) is $\frac{3}{2}R = 12.5\,\mathrm{J\,mol^{-1}\,K^{-1}}$. The monatomic gases helium and argon have molar heat capacities close to this value at room temperature.

QUESTIONS 65, 66

The mean kinetic energy of one molecule $= \frac{3}{2}\frac{R}{L}T = \frac{3}{2}kT$, where k is a universal constant called the *Boltzmann constant.*

$k = R/L$
$= 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$

At the same temperature the mean translational kinetic energy per molecule is the same for all monatomic gases and is equal to $\frac{3}{2}kT$.

Behaviour of gases

The kinetic theory of gases offers an explanation of many of the known properties of gases. These include Avogadro's Law, which states that equal volumes of gases at the same temperature and pressure contain the same number of molecules, Dalton's Law of partial pressures, and Graham's Law of diffusion.

A

Effects of intermolecular collisions

The average distance travelled by a molecule between collisions is called the *mean free path, λ.*

By considering the passage of a molecule having a finite diameter, d, in a gas containing n molecules per unit volume down an imaginary cylinder of radius d (the greatest distance away another molecule may be for a collision to occur) it can be shown that

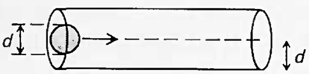


Figure A30
Mean free path of a molecule.

mean free path $\lambda \approx \dfrac{1}{\pi d^2 n}$

irrespective of the molecule's speed.

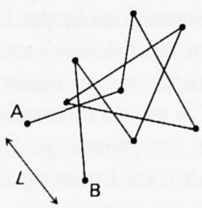


Figure A31
Molecular motion from A to B – a random walk.

For purely random motion between collisions, a molecule moves a distance L through the gas in time t given by $L = \sqrt{N}\lambda$, where N is the number of collisions made by the molecule in time t.

QUESTIONS 67, 68

At normal temperature and pressure, an air molecule of diameter about $3 \times 10^{-10}\,\mathrm{m}$ has a velocity of about $500\,\mathrm{m\,s^{-1}}$. It travels about $10^{-7}\,\mathrm{m}$ between collisions, making about 5×10^9 collisions per second. It would take a molecule more than a week to diffuse across a large room of still air.

Work done in expansion

QUESTION 69

Unit K, 'Energy and entropy'

When a gas expands reversibly at constant pressure by an amount ΔV, the work done by the gas is $p\Delta V$. (Reversible refers to an ideal process in which there are no losses due to friction, etc., and where a very small change in conditions will reverse the direction of the process.)

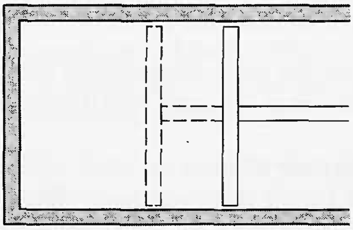


Figure A32

Randomness

Unit F, 'Radioactivity and the nuclear atom'

Unit B, 'Currents, circuits, and charge'

Unit K, 'Energy and entropy'

The kinetic theory of gases is just one of the topics in physics which involve the ideas of randomness and chance. Others include radioactive decay, the movement of electrons which constitutes a current in a wire, and the exchange of energy between atoms in a solid. Although the behaviour of an individual particle in such a system can only be predicted as a probability, it is possible to say quite precisely what the properties of the whole collection will be – if a large enough number of particles is involved.

Liquids

The liquid phase is much less well understood than either the solid or gaseous phases, and is a subject of current research. As a rule a substance is less dense as a liquid than as a solid (water is an important exception). The molecules in the liquid are, on average, slightly further apart than they are in the solid, and they have fewer nearest neighbours. There is some short range order, but not the long range order of a crystalline solid. A gas of course is completely disordered. In the liquid phase molecules, or groups of molecules, are free to move about at random; the speeds are lower than in the gas.

READINGS

MECHANICAL TESTING OF MATERIALS

To study the mechanical properties of different materials various types of test have been devised. Some, such as the tensile and hardness tests, can be used on all materials; but for materials which are brittle or weak in tension the compression test may be used.

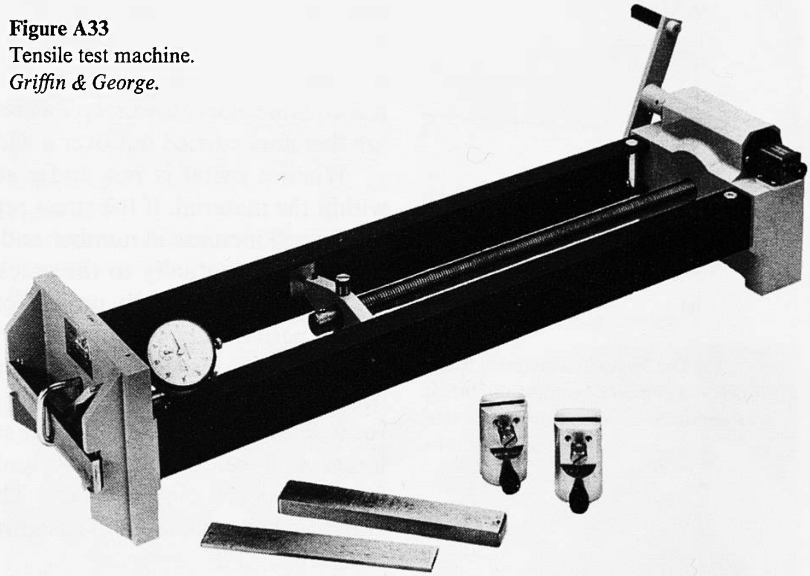


Figure A33
Tensile test machine.
Griffin & George.

The most widely used test in industrial and research organizations is the tensile test. An *extensometer* or tensile testing machine applies a controlled tensile force. The test sample has one of a number of standard shapes and sizes, defined by the British Standards Institute. It may be turned from a round rod or cut from a sheet. It has a narrowed centre section of marked length (figure A34). It is the extension of this length which is used to measure the strain. The machine stretches the specimen and measures the force needed to do so. Information about the *ultimate tensile strength*, the *ductility*, and the *yield strength* can all be found from the stress–strain curve. One of the disadvantages of the tensile test is that it destroys the specimen, and the tensile test can become relatively slow and expensive if a large machine is required to test a strong material.

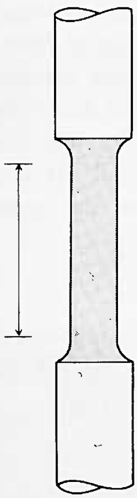


Figure A34

As materials get stronger they become harder. For some metals hardness is directly related to tensile strength. A hardness test can be quick and convenient. *Hardness* is defined as the resistance to penetration or abrasive wear. In most testers a small sphere or cone is forced into the surface of the specimen by a load for a fixed time. The hardness number is defined as the ratio of the applied load to the area of the indentation it causes. This number allows one material to be compared with others.

Figure A35
Hardness tester.
Griffin & George.

As well as struts and ties, rigid structures often contain beams or cantilevers which bear loads, tending to make them bend. Materials

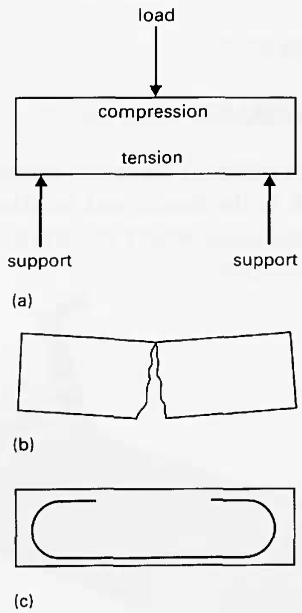


Figure A36
(a) The forces in a concrete beam.
(b) How a concrete beam would break.
(c) Reinforced concrete containing steel rods as shown.

must therefore be tested by bending. The specimen is subjected to both compressive and tensile forces at the same time and therefore bends. For example, concrete which has a high compressive strength but low tensile strength would fail the test shown. Steel rods strong in tension are embedded in the concrete for further reinforcement, hence the name *reinforced concrete*. The hooked ends of the steel rod transfer the load to the concrete. This is shown in figure 36.

Many substances suffer *creep*. A constant load is applied over a period of time. Creep is a very temperature-dependent property and becomes important at different temperatures for different materials. This can be critical if the material is bearing a load. On a hot day in a tropical country, the engineer could find that the structure he has built has collapsed because creep has become a significant effect. Creep tests are therefore carried out over a wide range of temperatures.

When a metal is put under stress, tiny cracks are likely to form within the material. If the stress repeatedly increases and decreases, the cracks will increase in number and may grow in size. Continuous stress cycles lead eventually to the cracks becoming visible. The strength of the material falls rapidly until fracture occurs. *Fatigue testing* normally uses a periodically varying stress for a long period of time. A simple tester might consist of a rod clamped in a ball race connected at the other end to a motor but slightly off axis. The rod flexes slightly as it rotates. After a large number of stress reversals, fracture can occur at forces well below the elastic limit of the material. At larger loads, fracture occurs more quickly. The time between the appearance of surface cracks and failure is usually very short.

Questions

a How many methods of mechanical testing are mentioned in the passage?

b Suggest how you might compression test a short ceramic pipe.

c In what units might hardness be measured?

d A diamond pyramid indentor measures a range of hardness values from 20 to more than 2000. Suggest materials that might be at either end of the scale. (*Hint:* Think of a girl in stiletto-heeled shoes walking over different floor surfaces in a house.)

e Why do you think a steel ball indentor cannot register accurately hardnesses of more than 350?

f How do the ends of the hooked rod in the concrete beam transfer the load to the concrete?

g Sketch a design for a simple fatigue tester.

LOOKING AT THE STRUCTURE OF MATERIALS

Of the hundred or more known elements, about 80 per cent are metals. Metals have a grain structure, formed when the liquid metal solidifies. Within each grain or crystallite the atoms are arranged regularly. The sizes and shapes of the grains of the material can vary greatly, depending on the purity and method of formation of the metal (figures A37 and A38).

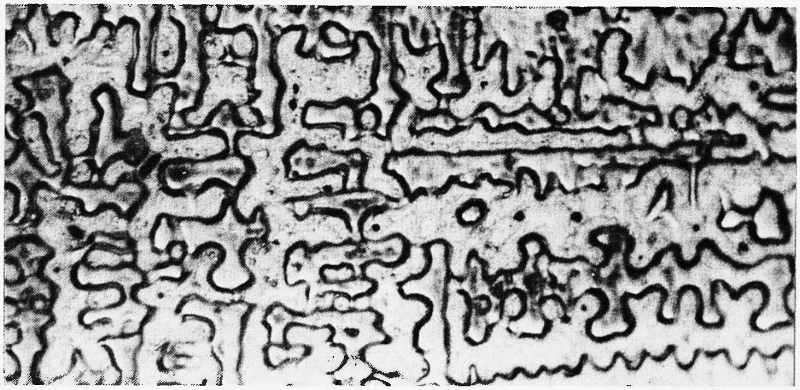


Figure A37
Cast bronze (5 % Sn; 95 % Cu), polished and etched (taken at × 400). Note dendrite-type structure (fern-like). If bronze is annealed, the structure looks like that shown for brass.
Dr A. A. Smith, Faculty of Engineering, King's College, University of London.

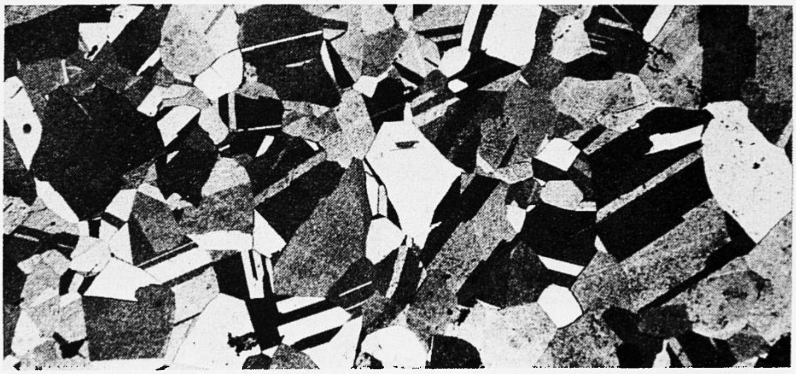


Figure A38
Brass (70 % Cu; 30 % Zn), polished and etched (taken at × 100).
Dr A. A. Smith, Faculty of Engineering, King's College, University of London.

Figure A39
The macrostructure of a cast metal. Large grains have formed at the centre of the ingot.
Dr R. T. Southin, School of Metallurgy, University of New South Wales.

Grains can be as small as 0.01 mm, but some are large enough to be seen with the naked eye (figure A39).

Optical microscopes, specially designed to observe reflected light from the chemically etched surface of metals, are used to examine the tinier grains, grain boundaries, and the structure of faulted and unfaulted materials. The incident light is often polarized to produce greater contrast and show the different orientations of the grains more clearly. Magnifications of up to × 2000 can be achieved, enabling details only 1 micron (10^{-6} m) apart to be distinguished. The parallel bands seen inside some of the grains in figure A38 are growth faults, called *twins*. The atomic arrangement within the band is the mirror image of the arrangement in the rest of the grain.

The different grain structures of steel, depending on the amount of carbon present and on the heat treatment during composition, can be seen in figures A40 to A43. Also contrast the grain structures of a metal after cold-working and after annealing (figure A44).

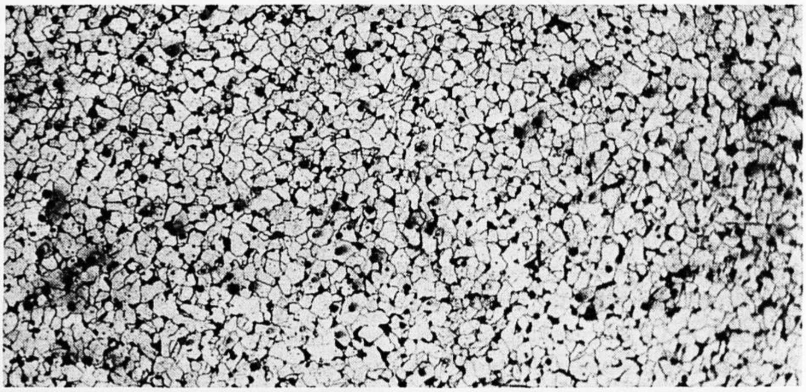


Figure A40
Steel (0.12 % C, taken at × 100). Note the ferrite grains and small dark regions of pearlite in the grain boundaries.
Dr A. A. Smith, Faculty of Engineering, King's College, University of London.

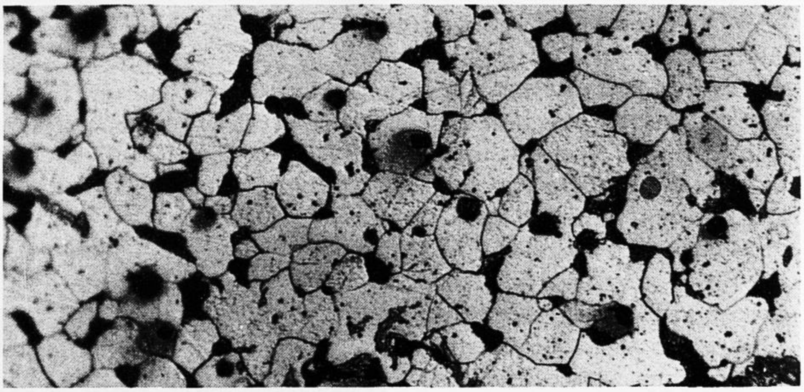


Figure A41
Steel (0.12 % C, taken at × 400).
Dr A. A. Smith, Faculty of Engineering, King's College, University of London.

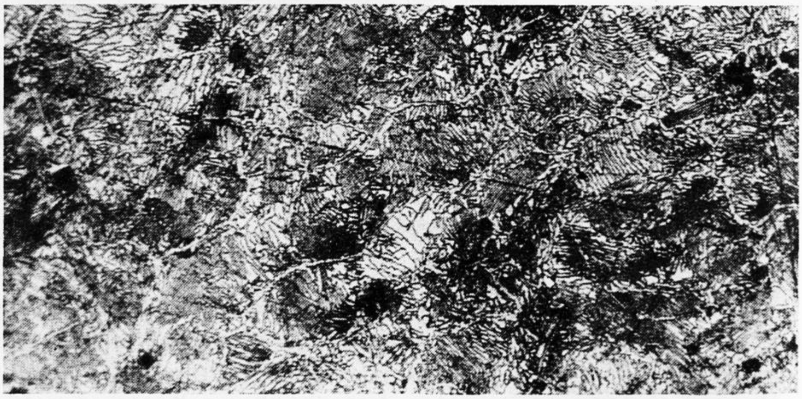


Figure A42
High carbon steel (1.2 % C), polished and etched (taken at × 400).
Dr A. A. Smith, Faculty of Engineering, King's College, University of London.

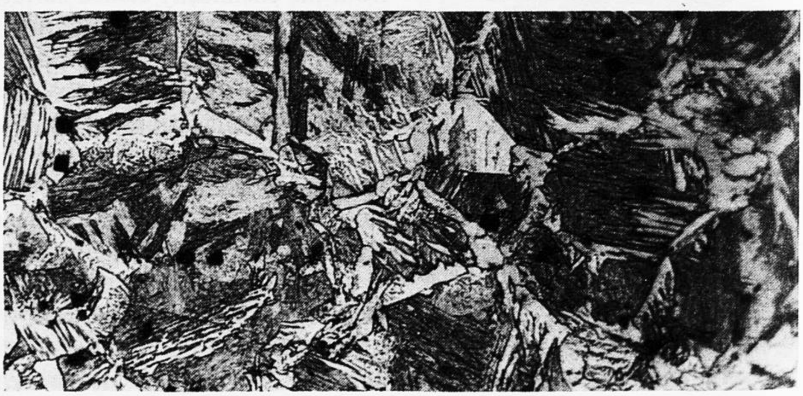
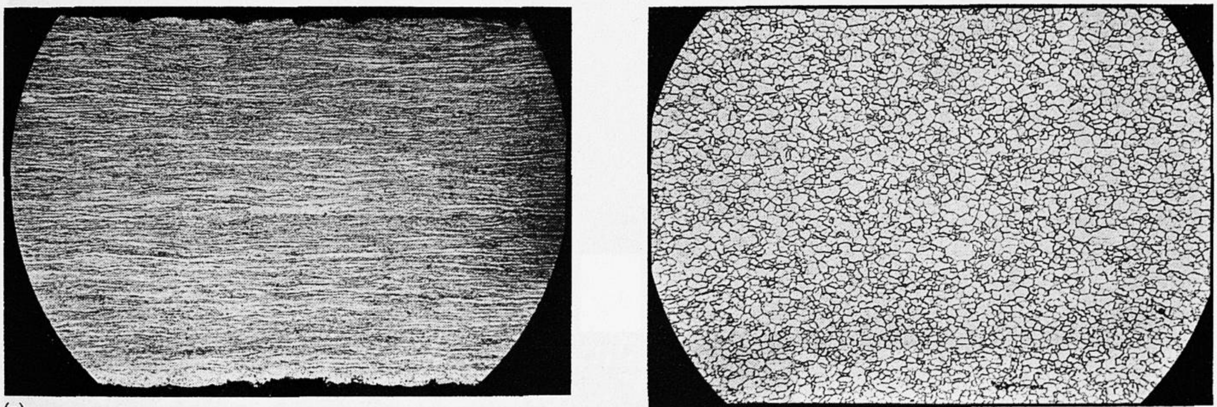


Figure A43
Steel (0.12 %C), quenched (taken at × 400). Note the changes in structure. The dark regions are oxide.
Dr A. A. Smith, Faculty of Engineering, King's College, University of London.

When a metal is plastically deformed the layer of regularly-spaced atoms within each grain can slip over each other, like shearing a pack of cards. These slip planes show up on the surface of a metal as a series of parallel edges, and can be seen in figure A45.

To detect imperfections on the atomic scale, such as dislocations in metal crystals, we need to use higher magnifications, that is $\times$ 20 000 to $\times$ 50 000. An electron microscope is used for this purpose. An extremely thin foil of metal is placed in the path of an electron beam and an image of the imperfections is produced on a fluorescent screen. Figure A46 shows the dislocation structure of a sliver of metal cut before it had been deformed. Figure A47 shows how the dislocations are entangled with each other after plastic deformation of the original aluminium specimen, causing work hardening. The dislocations are so interlocked that they are no longer able to move around.

Figure A44
(a) Grain structure of a metal specimen after cold-working.
(b) Grain structure of a metal specimen after annealing.
Welsh Laboratory, British Steel Corporation, Port Talbot.



(a) (b)

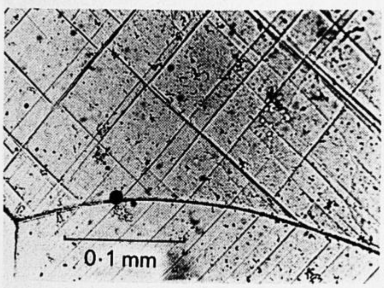


Figure A45
A specimen of aluminium showing slip.
Dr J. W. Martin and Dr J. M. Dowling, Department of Metallurgy and Science of Metals, University of Oxford.

Figure A46
Dislocation structure of a metal specimen before plastic deformation.
Welsh Laboratory, British Steel Corporation, Port Talbot.

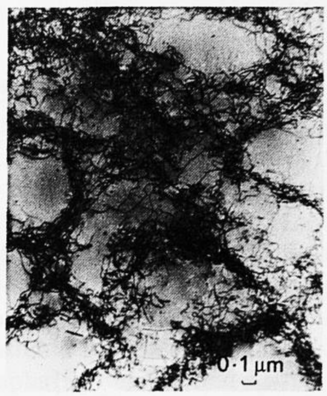


Figure A47
Electron micrograph of a thin foil taken from a crystal of plastically deformed aluminium showing dislocations tangled into 'cell' walls.
Dr J. W. Martin, Department of Metallurgy and Science of Metals, University of Oxford.

The electron micrograph of figure A48 is at a much greater magnification and shows up rows of atoms.

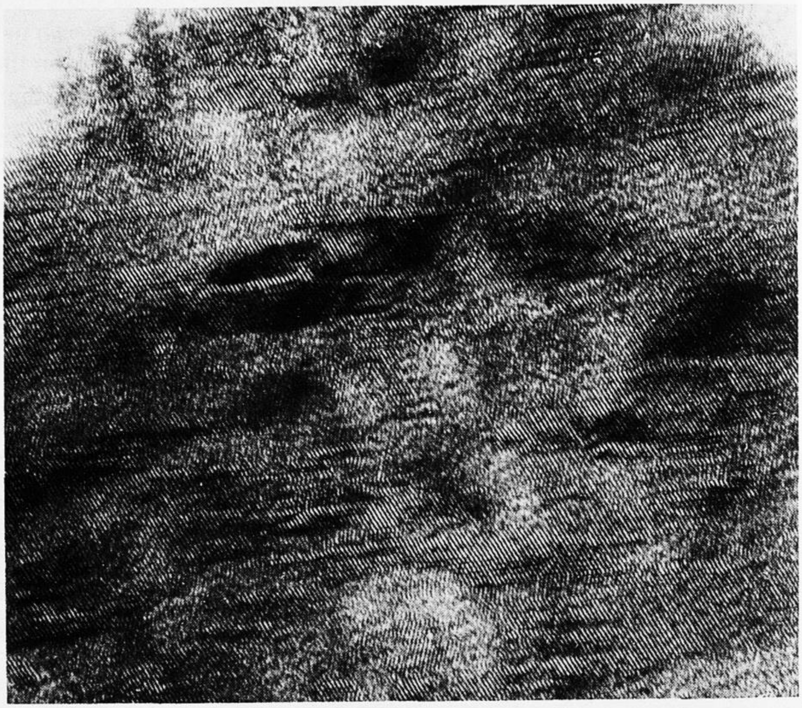


Figure A48
Electron micrograph of titanium dioxide. The planes of atoms are visible as patterns of lines in the photograph. Taken at × 3 400 000.
Dr Harvey Flower, Department of Metallurgy and Materials Science, Royal School of Mines, Imperial College of Science and Technology, University of London.

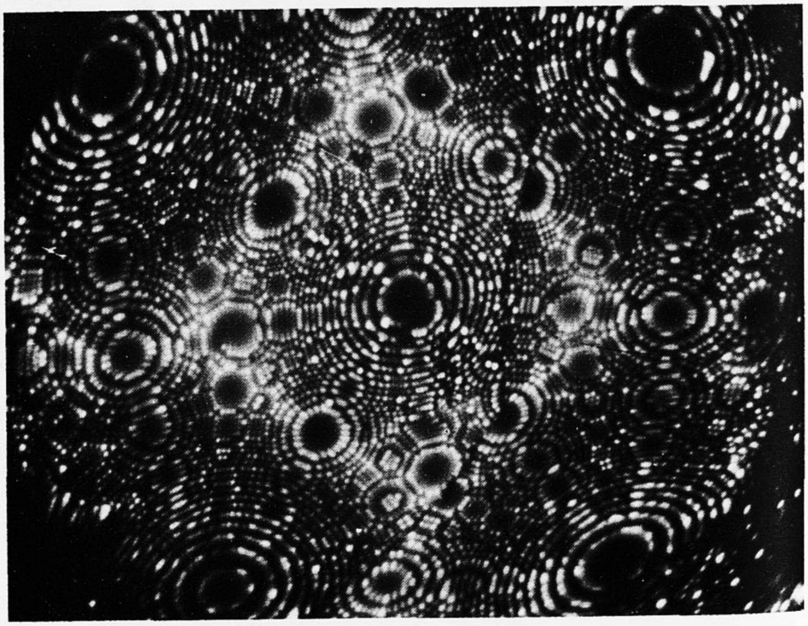


Figure A49
Field-ion micrograph of iridium showing a grain boundary.
Professor B. Ralph, Department of Metallurgy and Materials Science, University College, Cardiff.

The field-ion microscope has provided evidence of the regular arrangement of atoms in metal crystals. Gas ions are created close to the sharp point of the metal specimen, then accelerated away radially to hit a fluorescent screen and produce an image of the metal surface. More ions are produced near prominent atoms, so these points show up as bright spots on the screen (figure A49). A grain boundary between two crystallites is visible. Within each grain of the metal, the atoms are arranged in the same regular structure, but the relative orientation of the atoms between crystal grains is different.

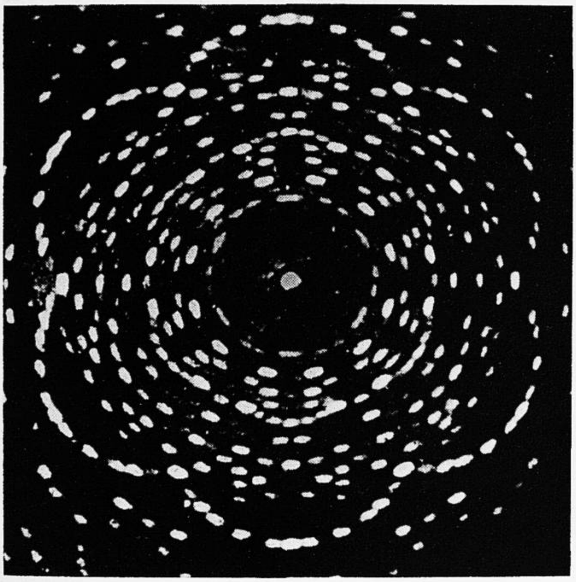


Figure A50
Von Laue pattern from an intermetallic compound of aluminium, iron, and silicon in the form of a single crystal.
Professor P. J. Black, Centre for Science and Mathematics Education, Chelsea College, University of London.

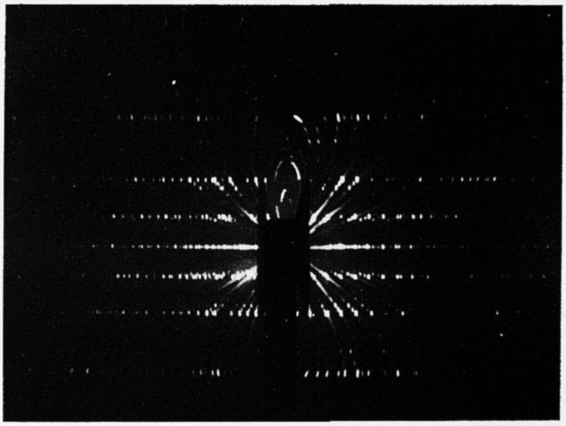


Figure A51
X-ray diffraction pattern for a single crystal (sucrose).
Department of Crystallography, Birkbeck College, University of London.

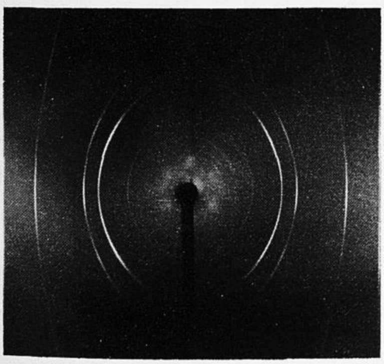


Figure A52
X-ray diffraction pattern for a polycrystalline metal (copper wire).
Department of Crystallography, Birkbeck College, University of London.

Other techniques, for example X-ray diffraction (see experiment A13 and Unit J, 'Electromagnetic waves'), show up the regular structure within each grain through a series of sharp rings or regular arrays of dots. The crystal structure and spacing between atoms can be determined from measurement of these patterns. Figure A50 shows the Laue pattern of an inter-metallic compound of aluminium, iron, and silicon in the form of a single crystal. Figures A51 and A52 are Bragg diffraction pictures of a single crystal (sucrose) and of a polycrystalline metal specimen (copper wire). X-ray patterns for glass and distilled water are shown in the next two photographs (figures A53 and A54).

The very fuzzy ring pattern or haloes indicate the lack of order within these substances, showing that glass is rather like a 'solid liquid'.

The final pictures (figures A55 and A56) are electron diffraction patterns (see experiment L7) of unstretched and stretched rubber. When rubber is stretched the jumbled-up long chain molecules are stretched out and line up partially, producing some measure of orderliness. This would explain the existence of the spots in figure A56 which do not exist in figure A55.

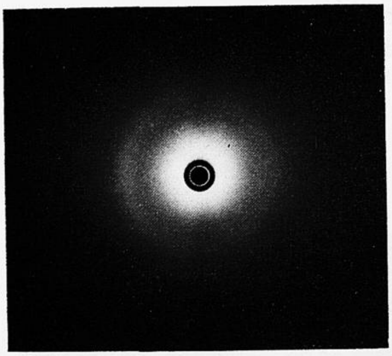


Figure A53
X-ray diffraction pattern for glass.
Pilkington Brothers P.L.C.

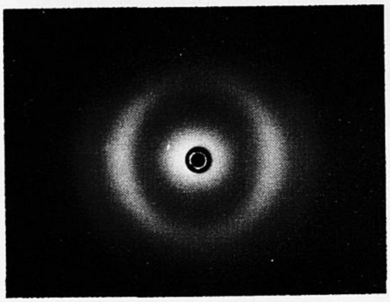


Figure A54
X-ray diffraction pattern for distilled water.
Pilkington Brothers P.L.C.

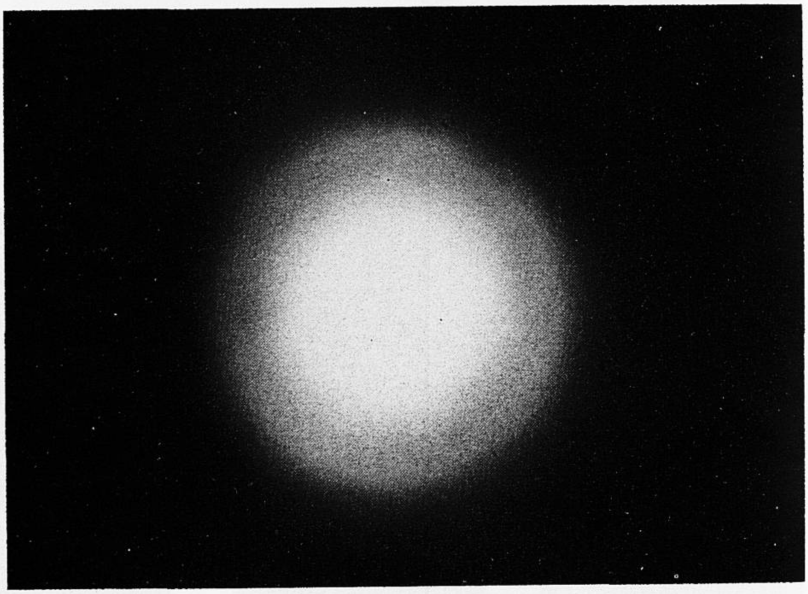


Figure A55
Electron diffraction pattern for unstretched natural rubber, showing only amorphous haloes.
The Malaysian Rubber Producers' Research Association.

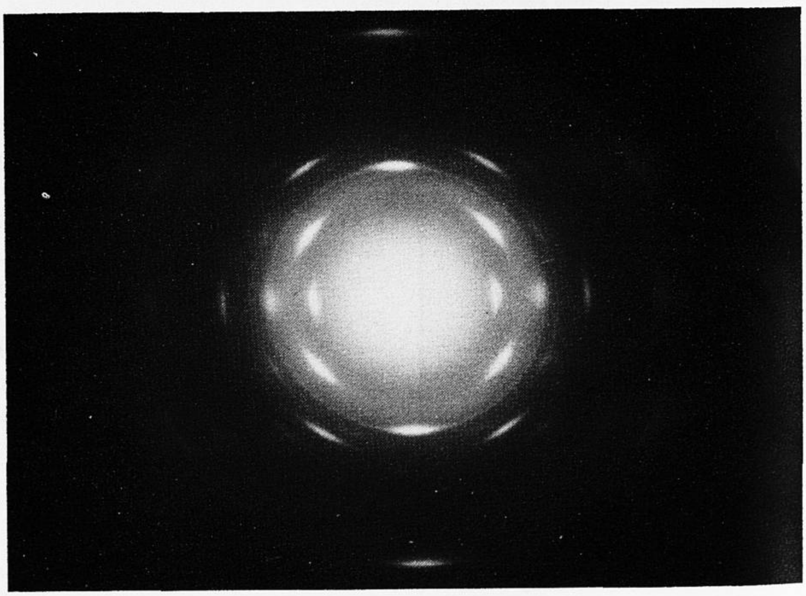


Figure A56
Electron diffraction pattern for highly stretched natural rubber, showing evidence of crystallization.
Professor E. H. Andrews, Department of Materials, Queen Mary College, University of London.

Further reading

MARTIN and HULL, *Elementary science of metals.* (Chapters 2 and 4.)
NUFFIELD REVISED ADVANCED CHEMISTRY Special Studies, *Metals as materials.* (Chapters 2, 3, and 5.)

Questions

a Twins are a common feature of pictures of the microstructure of metals. Why do twins have two parallel sides, unlike grain boundaries, which are irregular? How does this structure arise? (Look in one of the references.)

b Figures A40 to A44 include examples of the microstructure of metals which have been cold-worked, quenched, or annealed. How are the properties of the metal changed by these processes?

c In figure A45, why do the slip planes appear in different directions although the stress is only in one direction?

d What does an electron microscope look like? How large is it compared with an optical microscope? How large in area and how thick are the very thin metal specimens?

e Find out how a field-ion microscope works. (You may not fully understand the principle until you have studied Unit E, 'Field and potential'.) In figure A49 you are not looking at atoms directly. What are the bright spots on the picture?

f Explain why fuzzy rings and haloes in the X-ray diffraction pictures indicate lack of order, while sharp rings and spots indicate a degree of order in a solid structure.

MODELS

The following passage about models is an extract from Eric M. Rogers *Physics for the inquiring mind: the methods, nature, and philosophy of physical science* Copyright © 1960 by Princeton University Press and Oxford University Press. Excerpt reprinted by permission of Princeton University Press. (Chapter 24.)

We do not necessarily believe that the picture of nature we thus form *is* the real world. Many scientists say it is simply a *model* that works. It is easy to see that our picture of atomic structure is only a model – the invisible atom described in terms of large visible bullets and baseballs and large forces that we can feel like weights and the attraction of magnets. Yet it is uncomfortable to realise that we do not know what an atom is 'really like', and can only say that it 'behaves as if ...'. Moreover, with the progress of invention, microscope ... electron microscope ... ion microscope ..., you may decide that we can see real atoms and not just a model of them. Yet all such 'seeing' of the micro-world, however clear its results, is quite indirect: the images we obtain must be interpreted in terms of the models that guided our use of apparatus. In casual talk we gladly say, 'Now we know what the atoms are really like, how they are arranged and how they move about'; but in serious discussion, most scientists say, 'We have only shown that our model serves well, and we have obtained some measurements of parts of our model.' In a way, we use models in almost all our scientific thinking: atoms, molecules, gravity, magnetic fields, perfect springs, ...

Questions

a There are some models whose job is to remind one of what things are like: a model of a petrol engine, a circuit diagram, or a sketch map, for example. Do the models described above have anything in common with this type?

b Are there scientists who do not make use of models at all? Are there ways of using models other than in the way described above?

c In a sentence or two, indicate the differences between model and reality in some of the following examples:
i A model railway layout.
ii A railway map showing the lines neatly straightened out.
iii A model boat hull built for tests in a tank before building the real structure.
iv Molecular models used by chemists.
v The use of a computer to simulate the random flow of traffic, so as to improve the design of a road system.
vi Balls joined by springs to represent vibrating atoms in a solid.
vii An atom as a hard sphere.

d Is a mathematical equation of the vibration of two isolated atoms, for example an iodine molecule, a model in the same way that two air track vehicles, connected by a spring oscillating about their common centre of mass, are? Are all mathematical equations of physical situations only models?

THEORIES – TRUE OR NOT?

The following extract is by Karl Popper, who is a philosopher. He explains his view of scientific truth.

The way in which knowledge progresses, and especially our scientific knowledge, is by unjustified (and unjustifiable) anticipations, by guesses, by tentative solutions to our problems, by *conjectures.* These conjectures are controlled by criticism; that is, by attempted *refutations,* which include severely critical tests. They may survive these tests; but they can never be positively justified: they can neither be established as certainly true nor even as 'probable' (in the sense of the probability calculus). Criticism of our conjectures is of decisive importance: by bringing out our mistakes it makes us understand the difficulties of the problem which we are trying to solve. This is how we become better acquainted with our problem, and able to propose more mature solutions: the very refutation of a theory – that is, of any serious tentative solution to our problem – is always a step forward that takes us nearer to the truth. And this is how we can learn from our mistakes.

As we learn from our mistakes our knowledge grows, even though we may never know – that is, know for certain. Since our knowledge can grow, there can be no reason here for despair of reason. And since we can never know for certain, there can be no authority here for any claim to authority, for conceit over our knowledge, or for smugness.

From the author's preface to K. R. Popper *Conjectures and refutations*, Routledge & Kegan Paul Ltd, 1963.

Questions

a Rewrite the main points of the argument of this passage in your own words.

b 'Theories are nets: only he who casts will catch.' (*Novalis.*) Does Popper agree with this statement? If so, where in the passage?

c Discoveries come through learning to ask the right questions. How do we learn to ask the right questions?

A

MATERIALS USED IN ARCHITECTURE

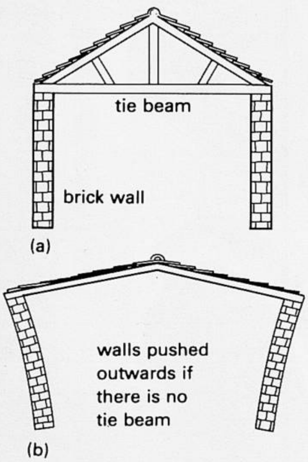


Figure A57

Figure A57(a) is a sketch of a conventional brick house, with a tiled roof carried on timber rafters. The brick walls are in compression, supporting the roof. The tie beam across the roof that prevents the roof from pushing the top of the walls outwards – see figure A57(b) – is in tension. An alternative way of preventing walls from bending uses compression, by providing buttresses outside the walls. The beautiful flying buttresses used by some cathedral builders are a fine example of the principle. (See figure A58.)

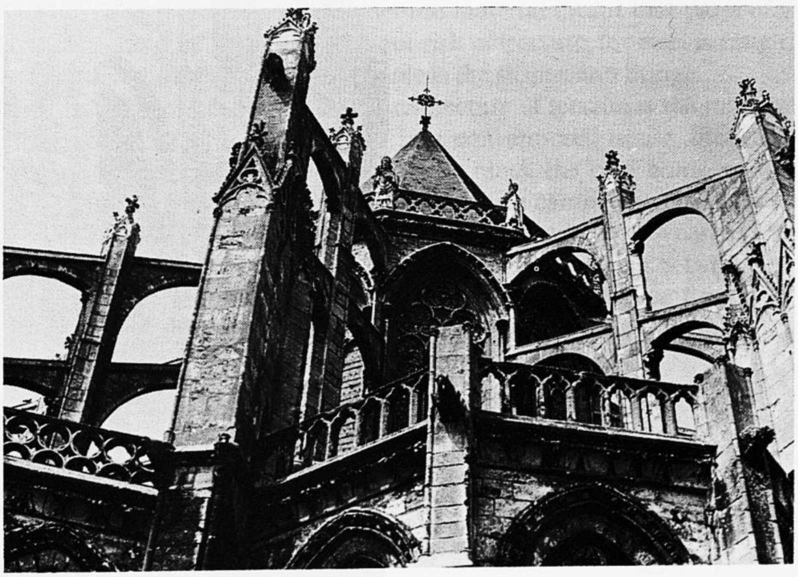


Figure A58
Tours Cathedral.
Clive Hicks.

The architecture of compression

Much early architecture relies mainly on compression for the stability of its buildings, because stone and brick are brittle materials good in compression but poor in tension. (Wood was for a long time the only tough material, good in tension, that was available in quantity. But wood rots, and was often avoided in buildings that were to be as permanent as possible.) The 'Romanesque' arch is a fine example of the architecture of compression, the compression often being expressed visually in the massive, thick pillars and short arches. (See figure A59.) Greek temples used stone columns in compression, carrying short thick stone beams bridging the tops of the columns. (See figure A60.)

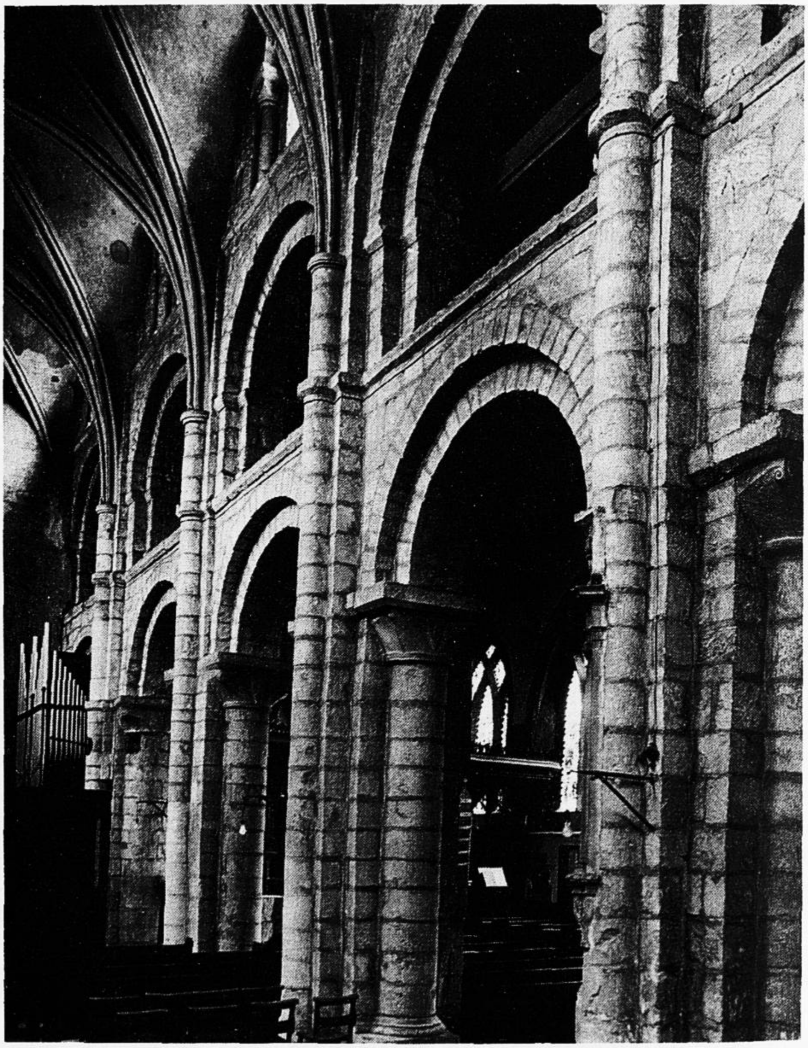
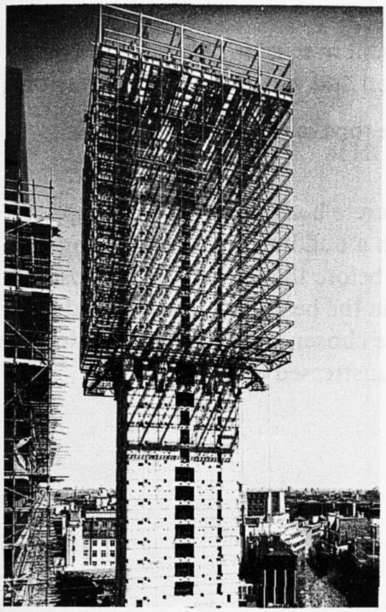
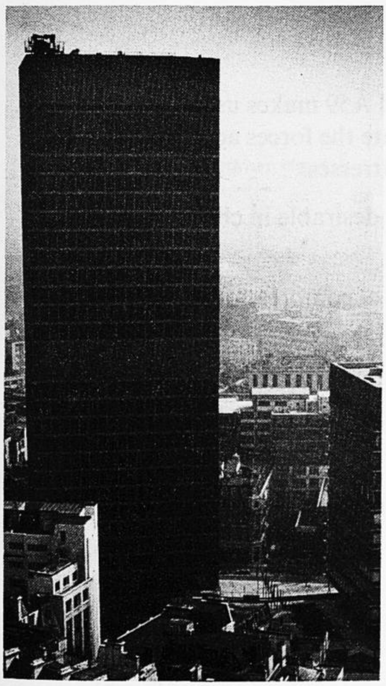


Figure A59
Blyth Priory.
Clive Hicks.



(a)



(b)

Figure A61
Construction photograph showing
(a) Top suspended structure of Commercial Union building in the City of London.
(b) Completed building.
The Architectural Press.

Figure A60
The Theseion, Athens.
J. Allan Cash Ltd.

The architecture of tension

The introduction of steel as a structural material meant that parts of a structure could be in tension without risk of fracture, for steel is tough, not brittle. The most obvious example is the suspension bridge.

A less obvious example of the architecture of tension is the modern tall tower block of offices or flats. In a conventional house, the walls hold up the roof; in one design of tower block the roof holds up the walls. The block has a central spine from which cantilever arms of steel or steel-reinforced concrete stick out. The top cantilever arm carries the roof, and the walls, often of glass in alloy frames, are hung between the lower arms. The arms also take the load of the successive floors, by withstanding bending forces. (See figures A61(a) and (b) and A62.)

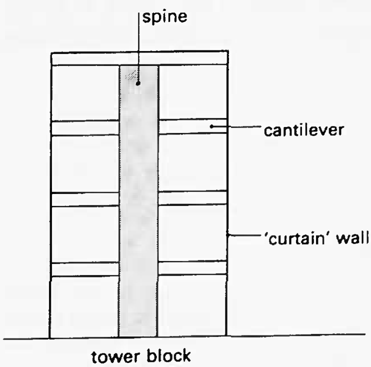


Figure A62

Questions

a Why is part of a beam that is being bent in tension? Sketch one beam and indicate which parts are in tension and which are in compression.

b Why had the stone beams joining the tops of columns in a Greek temple to be short and thick?

c Figure A63 shows a pre-stressed concrete beam being used to support both a floor and adjoining balcony in a building. Steel reinforcing bars are set in the concrete and tightened before the beam is put in position. Copy the figure and indicate where, in the beam, two rods should be put and justify the positions you have chosen. What advantage does this pre-stressed concrete have over unstressed concrete?

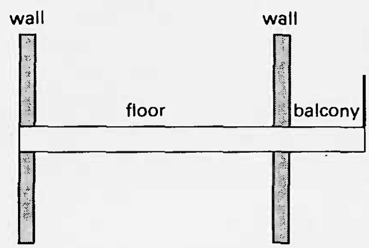


Figure A63

d The arch structure of figures A58 and A59 makes use of the compressive strength of stone. Indicate the forces acting on an arch and hence justify the use of flying buttresses.

e What properties would you consider desirable in choosing a material or materials for a road bridge?

f Give some other examples of the use of compression and tension in architectural structures.

g Fit the modern motorway flyover into this pattern.

h How are large domes built? Are the internal forces similar to those in an arch?

i 'The tree is nature's precursor of the modern office block.' Does this make sense?

LABORATORY NOTES

EXPERIMENT

A1a The stretching and breaking of metals to compare strength, ductility, and hardness

Selection of materials:
stainless steel wire, 1 m lengths, 0.08 mm diameter
copper wire, 1 m lengths, 0.28 mm diameter
other metal wires, *e.g.*, iron, nichrome, fuse wire, etc., as available
selection of metal strips about 100 mm × 10 mm × 1 mm, *e.g.*, copper, steel, aluminium.

G-clamp, small
Hoffman clip
2 wooden blocks, about 20 mm × 20 mm × 10 mm, and 2 strips, about 60 mm × 10 mm × 5 mm
2 dowel rods, 1–2 cm diameter; 10–15 cm long
retort stand base, rod, boss, and clamp
centre punch
plastic, card, or metal tube (about 30 cm long, to take centre punch)
hand lens
safety spectacles

A

Safety note: Take care when doing experiments which involve stretching wires or breaking brittle materials. If the specimen suddenly breaks it may fly up into your face. Wear eye protection.

Samples of different metals are available in wire and thin sheet form. Apply forces to the specimens to observe their behaviour in different situations: stretching (tensile forces), flexing, scratching, and hitting (impact hardness).

Examine, with a hand lens, the broken ends of a wire or the impact or scratch on a sheet.

Various terms are used to describe the different behaviours of the metals. For each sample you have tested, classify it using some of the following terms: strong, weak, hard, soft, ductile, brittle, rigid, tough, malleable, flexible, elastic, plastic. (Some definitions are given on pages 3 and 4, or use a reference book.) For example, a steel wire is strong in tension; it is ductile, elastic, and suffers brittle fracture.

Suggest a use for each of the specimens and say why the chosen metal is particularly appropriate for this use. What metal might be suitable for toothpaste tubes (malleable) but not suitable for beer cans?

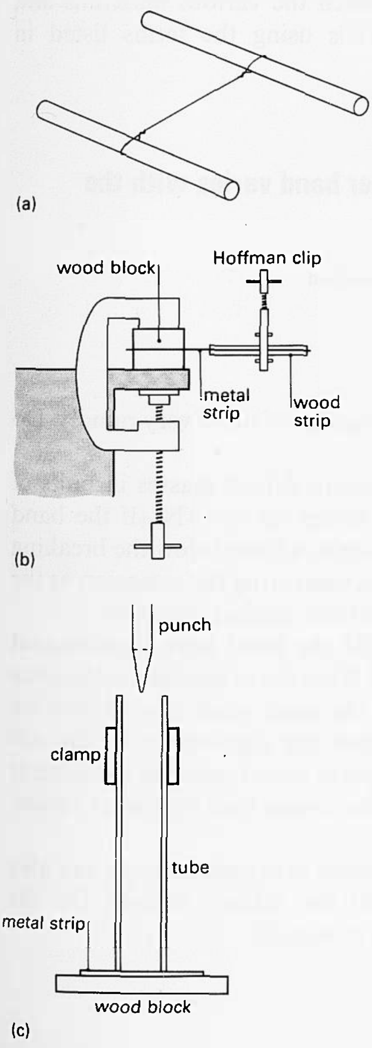


Figure A64
Simple testing of metals.
(a) Stretching.
(b) Bending.
(c) Hardness.

c the value of the food produced per head per year; and predict how figure G12 would be changed if these quantities were taken into account. (Your answers to question **3** will give a reasonable guide to some of these answers.)

Characteristics of fuels

21(E) Consider a family (of four people) in the U.K. whose domestic fuel requirement is 10^{11} J per year.

a Assume for the moment that the requirement is entirely for heating.

Estimate what quantities of the following resources are required to provide for their needs. Would each be a feasible solution for the needs of the U.K. population of, say, 55 million?

i Forest, assuming that temperate forests produce 700 tonnes of dry material suitable for fuel per km^2 per year. The energy equivalent of wood varies widely: assume it is $3\,kW\,h\,kg^{-1}$.

ii Miners, assuming that each miner produces 500 tonnes of coal per year.

iii Area of solar panels, assuming that the average insolation (the measure of solar radiation falling on a unit area per unit time) is $10\,MJ\,m^{-2}\,day^{-1}$ in the U.K. and the efficiency of solar panels is 40 per cent.

b Assume that it is feasible to use the resources in **a** to generate electricity. What difference, if any, would be made to your answers if the 10^{11} J were provided by electricity?

22(E) In which sector(s) in table G5 (page 419) could fuel most easily be saved? Would it be possible to save 20 per cent of the total?

If 20 per cent could be saved overall in the industrialized nations, what would be the effect on global fuel consumption, and on the lifetimes of fuel resources? (You will have to make some assumptions about the other changes which will be occurring at the same time – it is easiest to start by assuming that fuel consumption would otherwise stay constant.)

23(P) Many fuels are produced far from where they will be used. Table G14 shows the cost of moving them by various means.

Calculate the percentage energy loss in the following situations:

a transporting oil by pipeline from the North Sea to the U.K. (100 km);

b transporting coal from the Siberian coal fields to Moscow by heavy train (3000 km);

c transporting oil by supertanker from the Middle East, round the Cape to Western Europe (25 000 km);

d transporting oil by small tanker from the Middle East (via the Suez Canal) to Western Europe (15 000 km);

EXPERIMENT

A1b A preliminary study of the force–extension relationship for lengths of various materials

rubber bands
thin rod of Plasticine
paper
polythene (*e.g.*, from a food bag)
nylon line
strip of expanded polystyrene
steel wire, copper wire, 2 dowel rods — as in A1a
safety spectacles
plastic ruler

Pull the various materials provided, using the two dowels where necessary, and sketch graphs of applied force against extension for each specimen. You should wear safety spectacles.

Compare the forces required to stretch the various materials and then break them. Classify the materials using the terms listed in experiment A1a.

EXPERIMENT

A2a A study of how the length of a rubber band varies with the applied force

size 32 rubber band, 75 mm × 3 mm × 1 mm unstretched
hanger and slotted masses, 0.1 kg, up to 2 kg
retort stand base, rod, boss, and clamp
metre rule

Stretch and release the rubber band a number of times very rapidly. Do you notice any physical change(s)?

Hang the rubber band from the clamp. Attach masses in units of 0.1 kg and measure the extension for forces up to 15 N. (If the band breaks below this applied force, repeat up to a force below the breaking force.) Remove the masses one at a time, measuring the extension as the load is reduced. Plot a graph of applied force against extension.

Study the shape of your graph. Did the band have a permanent extension at the end of the experiment? Were the extensions as the force decreased equal to the extensions for the same value of applied force when it was increasing? Can you suggest any significance for the size and shape of the resulting loop? If you have time, repeat the experiment loading the band to only 0.4 of the maximum load you used before. Compare the shape of the two graphs.

Some of the terms applied to the metals of experiment A1a can also be used to describe the behaviour of the rubber. Which? Do the properties of the rubber change as it is stretched?

EXPERIMENT

A2b The stretching of a nylon fishing line or a strip of polythene

nylon fishing line (breaking load about 10 N), 1.5 m long
retort stand base, rod, boss, and clamp
hanger with slotted masses, 0.1 kg
polythene strip, 200 mm × 10 mm, (*e.g.* 500 gauge, about 0.1 mm thick)
2 polarizing filters, 50 mm × 50 mm
adhesive tape
metre rule
safety spectacles

Nylon

Safety note: Take care when stretching filaments. If the specimen suddenly breaks it may fly up into your face; it is advisable to wear eye protection.

Tie together the two ends of the fishing line to make a loop about 0.75 m long. Make the knot carefully, and test it to see that it does not slip. Hang the loop from the clamp and carefully attach masses in steps of 0.1 kg up to 0.8 kg, measuring the extension each time. Remove the masses one by one, again measuring the extension.

Draw a graph as in experiment A2a, and answer the same questions.

How will the behaviour of an angler's fishing line differ from the behaviour of the short sample you have used? What factors will be the same? You might like to find the maximum extension of the nylon which will permit it to return to its original length. A more useful quantity to know is the strain, the extension divided by the original length.

Imagine what would happen if you tried the same experiment using a strand of wool (try it if you wish). You can now suggest why nylon garments last longer than woollen ones. Other properties, however, make wool a better material for some applications. Suggest some.

Polythene

Make sure the polythene is cut with clean and not ragged edges. Devise some simple method to hang up the strip and stretch it using the masses. Watch what happens very carefully. When you have stretched it, put the strip between crossed polarizers and look for stress patterns.

EXPERIMENT

A3 Measurement and prediction of the breaking force for aluminium samples

strip of aluminium (kitchen) foil, 100 mm × 10 mm
micrometer screw gauge or Vernier calipers
ruler
strip of aluminium sheet, 100 mm × 10 mm × 1 mm
adhesive tape
spring balance, 10 N, or hanger with slotted masses, 0.1 kg

A

Use paper and adhesive tape to make 'handles' to enable you to find a value for the force required to break the aluminium foil by pulling along its length.

Measure the thickness of the aluminium foil and of the sheet and estimate how many strips of foil would be required to make the sheet. Hence estimate the force which might be required to break the sheet. Estimate an uncertainty in this value as follows. What is the maximum percentage uncertainty in your estimates for:

i the foil breaking force
ii the foil thickness
iii the sheet thickness?

Add all three of these together to find the maximum percentage uncertainty in the calculated force. (See 'Calculation of uncertainty' on page xvi.)

To estimate the force you assumed the breaking stress would be the same for both the sheet and the foil. Suppose you had been given a sheet of twice the width, how would the breaking force have varied? Would the breaking stress still have been the same?

Can you suggest any reasons why your prediction is likely to be too high or too low? Later, when you have studied how defects in the structure of materials affect their strength, you may be able to give a better answer to this question. The uncertainty you were asked to calculate above is a *random* error. Some of your suggestions may involve *systematic* errors.

EXPERIMENT
A4 Measuring the breaking strength of a glass fibre

soda glass rod, 0.2 m long, about 3 mm diameter
retort stand base, rod, boss, and clamp
Bunsen burner
micrometer screw gauge
hanger with slotted masses, 0.1 kg
hand lens
string
safety spectacles

Safety note: Remember to wear safety spectacles.

Hold the top of the glass rod vertically in the clamp so that it is about 0.75 m above the bench or floor. Tie a 1 kg mass to the lower end with string. (A clove-hitch is suitable.) Support the mass with one hand and heat the middle of the glass over as short a length as possible until it is red hot. The lower part of the rod may need to be supported. Remove the flame and release the mass. The result should be a straight glass fibre with a length of glass rod at each end.

Hang masses from the fibre to find the breaking force. By how much does the fibre stretch?

Observe the broken ends of the glass fibre using a hand lens and contrast the point of fracture with that seen for a copper wire in experiment A1a. How do the two fractures differ? Explain the different behaviours using the terms for describing materials introduced in experiment A1a. Measure the diameter of the fibre carefully at the place where it broke.

Using the same method as for experiment A3, estimate the maximum load which the glass rod could support. The result of the calculation should show you that glass is very strong. Is glass used as a strong material? If so, where? What is the major difficulty with glass?

EXPERIMENT
A5 Measuring the strength of paper

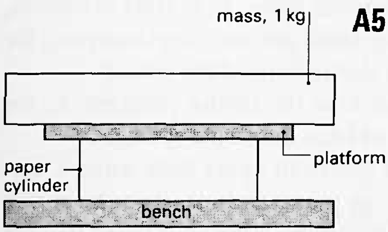


Figure A65
Measuring the strength of paper.

sheet of thin paper, A4
sheet of corrugated paper, at least 30 mm × 200 mm
hardboard square, about 80 mm × 80 mm
2 masses, 1 kg
10 slotted masses, 0.1 kg
adhesive tape
raw potato
paper drinking straw
metre rule

Cut several strips of paper about 30 mm wide, and make paper cylinders about 50, 60, and 70 mm in diameter.

Using the corrugated paper (or plain paper folded concertina-fashion), make a similar cylinder about 60 mm in diameter.

Using the hardboard square as a platform, load each of the paper cylinders centrally, carefully, and gently with masses until it collapses. Repeat with the corrugated paper cylinder.

What factors affect the strength of each cylinder? Why is the corrugated paper cylinder so much stronger?

What is the area of the paper which is supporting the load in each case? Is there a relationship between the load and the area of paper? Could you define a term *crushing strength* for the paper? Do you have enough data to decide? If not, how would you proceed to be able to give an answer? How would you re-design the experiment to avoid some of the present difficulties?

Can you predict the load that a paper cylinder of diameter 120 mm would support? Is your prediction likely to be too large or too small?

Take a raw potato. Hold it between your fingers and thumb so that the top and bottom are clear. Hold a paper straw firmly in your other clenched fist and thrust it very rapidly and firmly at the potato with a 'karate' chopping action. Do not check your swing but make a determined effort to drive the straw right through the potato.

Estimate the force exerted by the paper straw. Why did it not buckle as would be predicted by the investigation above on the strength of paper?

EXPERIMENT

A6 A short investigation of spring behaviour

4 expendable steel springs
hanger with slotted masses, 0.1 kg
retort stand base, rod, boss, and clamp
short length of stiff wire (*e.g.*, from coat hanger, or 0.9 mm diameter copper)
stop watch

i Each spring should obey Hooke's Law, $F = kx$, for small extensions, x, of the spring. By plotting a graph of applied force, F, against extension, x, find the spring constant, k (restoring force per unit displacement), for one of the springs. Do not exceed the elastic limit of the spring.
ii Connect two springs in series. Find how the spring constant, k_s, for this system (that is $F = k_s x$) is related to k for the single spring.
iii Connect two springs in parallel as shown in figure A66, using a 'zig-zag' piece of wire to couple them to the mass, and measure the spring constant, k_p, for this system. How is this spring constant related to k for the single spring?

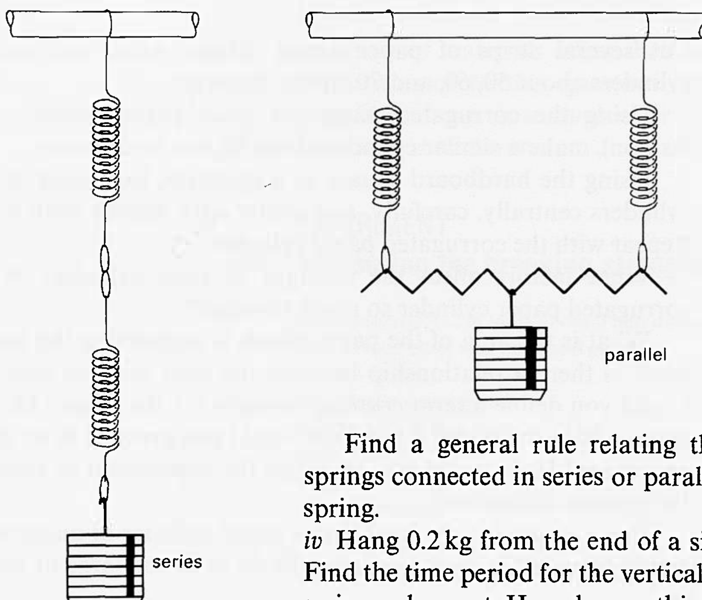


Figure A66
Springs in 'series' and in 'parallel'.

Find a general rule relating the spring constant of a system of springs connected in series or parallel to the spring constant of a single spring.
iv Hang 0.2 kg from the end of a single spring, pull down and release. Find the time period for the vertical oscillation. Connect four springs in series and repeat. How do you think the period of oscillation is related to the spring constant? Check your prediction by using two springs in series.
v Compare the periods for the vertical oscillation of 0.4 kg and 0.1 kg masses suspended from the end of two springs connected in series. How is the period related to the mass? Check your prediction using other masses.

You have now determined how the period of oscillation, T, varies with m, the mass, and k, the spring constant for a spring. What are the units of m and k? Does your expression for T in terms of m and k have the units of time? If it does not, your prediction is either wrong or incomplete, that is, the period of oscillation depends on other measurable quantities, such as the length of the spring.

DEMONSTRATION
A7 The effect of cracks

Bunsen burner
3 lengths of soda glass, 0.1 m, about 3 mm diameter
file, *e.g.*, triangular
matchstick
2 strips of polythene, 100 mm × 10 mm (*e.g.*, 500 gauge, about 0.1 mm)
scissors
safety screen
Perspex strip, 250 mm × 10 mm × 6 mm (clear faces 6 mm wide)
2 polarizing filters, 50 mm × 50 mm, or liquid crystal display filters, 105 mm × 35 mm
slide or overhead projector
safety spectacles

A

A7a A glass rod can be cut by making a file mark and bending the rod across the crack. Why does this work? Why does glass snap cleanly?

A7b Stress concentration may be shown by projecting the image of a nick cut in a strip of polythene or adhesive tape and held between crossed polarizers. A strip without a nick is stretched first, to show that colours develop as the strip is stretched.

A7c Why are equally-spaced lines seen across the Perspex strip when it is flexed between crossed polarizers? How can this help to explain why a bent glass fibre may break if touched on the outside but not on the inside?

EXPERIMENT
A8 Measurement of the Young modulus and breaking stress of a wire

G-clamp
2 wooden blocks
single pulley on clamp
metre rule
adhesive tape or gummed paper tape
hanger with slotted masses, 0.1 kg, up to 2 kg
micrometer screw gauge
safety spectacles
lengths of iron wire, 0.20 mm diameter
lengths of copper wire, 0.28 mm diameter
lengths of steel wire, 0.08 mm diameter

Choose one of the metal wires. Devise a careful, simple (and safe) experiment to obtain a stress–strain graph, and values within stated limits for the Young modulus and the breaking stress of the metal.

Arrange your apparatus horizontally across the bench. What length of wire should you stretch?

Steel, especially, is springy. Make sure you have a safety device to stop an end whipping back when the wire breaks; and wear safety spectacles.

How will you measure the extension of the chosen length of wire accurately? Why should you measure the diameter of the wire in several places and take readings at right angles in each place?

From your graph find the Young modulus for the wire and estimate the uncertainty in your value. Which of the measurements you have made gives the largest contribution to the uncertainty? What is your estimate for the breaking stress of the wire?

Would you expect the Young modulus for a bar of the metal you have used to have the same value as you have found for the wire?

On your graph, identify the elastic limit and estimate the percentage strain the wire can withstand before its elastic limit is reached.

Decide whether it would be better to design two different sets of apparatus to investigate:

i the properties of the wire up to its elastic limit, and

ii its properties from its elastic limit to its breaking stress.

EXPERIMENT

A9 Testing the formula for translational kinetic energy

A9a Catapulting an air track vehicle

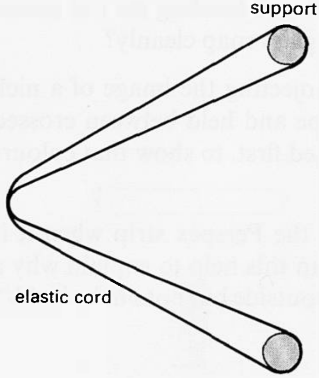


Figure A67

air track and accessories
air blower
timer, resolution 1 ms
photodiode assembly with light source
metre rule
3 elastic cords for accelerating vehicle
thin card
balance, 1 kg

An elastic catapult is made from a rubber band or cord by stretching it tightly between two firm supports as shown in figure A67, at such a height that it will project a vehicle along the air track. Catapult the air track vehicle with one, two, or three elastic bands or threads all at the same stretch, so that the vehicle is given one, two, or three units of kinetic energy.

Measure the speed of the vehicle. Also alter its mass to test the expression for kinetic energy: $\frac{1}{2}mv^2$.

A9b Measurements with potential energy changing to kinetic energy

either

i

Apparatus as experiment A9a (air track, etc.) with:
hanger and slotted masses, 0.01 kg
string
single pulley

or

ii

runway
2 dynamics trolleys
single pulley on clamp
string
hanger and slotted masses, 0.1 kg
ticker-tape vibrator
carbon paper disc
ticker-tape
transformer
balance, 2 kg

i Air track: level the air track carefully, and then use a falling mass to accelerate the air track vehicle. Use the photodiode assembly and timer to measure the vehicle's speed, v, at different distances, h, fallen by the mass.

ii Trolley and runway: compensate the trolley runway carefully for friction without the string connected. Attach 0.4 kg to the end of the string and accelerate the trolley using the falling mass. Make sure you catch the trolley before it comes off the edge of the bench. Use the ticker-tape to find the speed of the trolley, v, at different distances, h, fallen by the mass. You only need one ticker-tape.

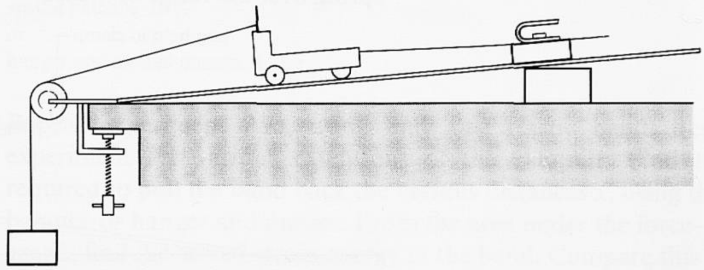


Figure A68

i and *ii* Plot graphs of v against h, and v^2 against h. How does your straight line graph show that the kinetic energy is proportional to v^2?

What is the total mass being accelerated in your experiment?

Change the value of the falling mass and/or use more trolleys stacked together (or a train of air track vehicles) to show how the kinetic energy depends on mass.

Does the small change in gravitational potential energy as the trolley moves down the sloping runway lead to an error in the kinetic energy? If not, where has this energy gone?

EXPERIMENT
A10 Measuring the elastic strain energy stored in a spring

Method 1

runway
dynamics trolley
expendable steel spring
spring balance, 10 N
retort stand base, rod, boss, and clamp
G-clamp

either
ticker-tape vibrator
carbon paper disc
ticker-tape
transformer

or
timer, resolution 1 ms
photodiode assembly with light source
metre rule

Compensate the trolley runway carefully for friction. G-clamp the retort stand to the bench and use the rod and clamp to hold a trolley peg vertically over the middle of the runway. Its lower end should be a few millimetres higher than the peg in the trolley. Hook the spring over the two pegs, pull back the trolley, and release it. The spring should fall from the fixed peg as the trolley passes.

Measure the extension of the spring, x, and the final speed of the trolley, v, for extensions of the spring up to 120 mm. Calculate the kinetic energy given to the trolley in each case.

Use the spring balance to obtain a force–extension graph for the spring over the range of x used.

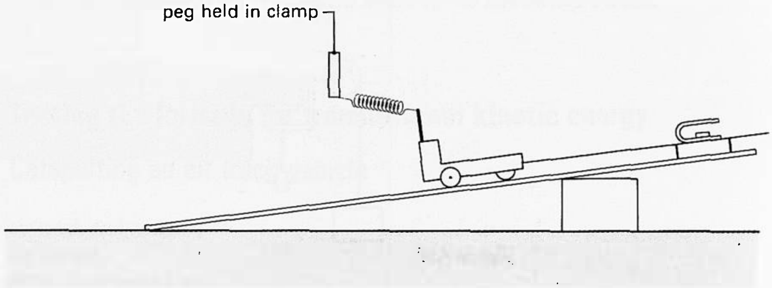


Figure A69

Method 2

Apparatus as for method 1 except for:
dynamics trolley with spring plunger
balance, 2 kg, or masses, 1 kg
wooden block at least 8 cm high
adhesive tape
graph paper

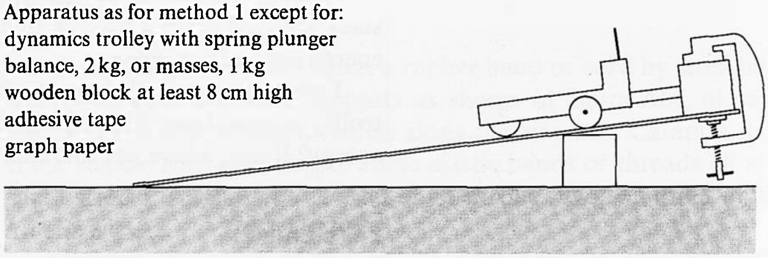


Figure A70

Calibrate the trolley's spring plunger as follows. Make a scale on the plunger (using adhesive tape and a graph paper strip for example). Note the zero compression position, and measure the force required to compress the plunger through various distances. Plot a graph of force against compression distance.

Set up a friction-compensated slope and firmly G-clamp a block to it. The trolley spring can be compressed to known distances, x, by pushing against the block. Measure the maximum velocity, v, attained by the trolley for several compression distances and then calculate its kinetic energy.

For either method compare the values of $\frac{1}{2}mv^2$ with the area under the appropriate part of the graph of force against distance. Are they equal within the limits of the experiment? If the graph is a straight line, show that the maximum velocity, v, should be proportional to the spring compression or extension, x. Plot a graph to check whether this is true in your experiment.

Suggest why a part of the elastic energy originally stored in the spring is not transformed into kinetic energy of the trolley. Estimate the fraction of the elastic strain energy not transformed into kinetic energy.

EXPERIMENT
A11 Changing elastic strain energy into gravitational potential energy or translational kinetic energy

A11a

Apparatus as for experiment A9a, plus:

either
spring balance, 10 N
or
hanger and slotted masses, 0.1 kg

Repeat experiment A9a, using only one elastic band. Repeat the experiment for various extensions of the catapult. Find the force required to pull the band back the various distances x, using the spring balance or hanger and masses. From the area under the force–distance graph, find the stored strain energy in the band. Compare this with the final kinetic energy of the vehicle.

Are the two energies equal for each value of x?

A11b

steel nail, 100 mm, or equivalent mass of wire, 10–15 g, bent into shape of horseshoe staple
retort stand base, rod, boss, and clamp
card or board
metre rule
hanger and slotted masses, 0.1 kg
rubber band (size 32, *i.e.*, 75 mm × 3 mm × 1 mm unstretched)
safety spectacles
balance, 0.1 kg

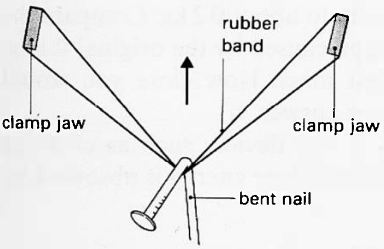


Figure A71

Safety note: Wear safety spectacles: the nail may fly up in to your face.

i Stretch the rubber band between the jaws of the clamp so that it makes a narrow horizontal loop. Place the bent nail across both strands and fire it vertically upwards about 0.5 m to 1.0 m.

Use the hanger and masses to obtain a force–distance graph for the rubber band and hence find the energy stored in the band from the area under the curve.

Compare the maximum gravitational potential energy of the nail with the elastic strain energy of the stretched rubber band.

ii Instead of firing the nail into the air, stretch the rubber band over the end of the rule to make a narrow vertical loop, so that when you release the band it rises about 1.0 m. Compare the maximum gravitational potential energy of the band with its elastic strain energy when stretched, found by a similar method to part *i*.

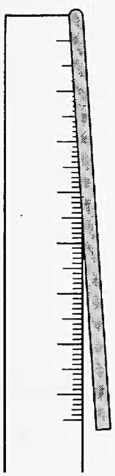


Figure A72

Can you suggest why the force–extension graphs for the rubber band in parts *i* and *ii* are different?

Contrast the two versions of experiment A11b. Which, do you think, will be more
a accurate,
b reliable, that is, give consistent results?

A

One student measured the force F_{max} required for maximum extension x_{max} in experiment A11b*ii* and estimated the elastic strain energy from $\frac{1}{2}F_{max}x_{max}$. How close would you expect the calculated and measured heights reached by the rubber band to be? Justify your answer.

In any of experiments A11a, b*i*, or b*ii* the energy stored as elastic strain energy is likely to be larger than the maximum kinetic or gravitational potential energy. Why is this?

EXPERIMENT
A12 Energy absorbed in deformation

iron wire, 1.0 m long, 0.71 mm diameter
plastic tube, wooden rod, or similar, about 35 mm diameter, and at least 10 cm long
hanger with slotted masses, 0.01 kg
retort stand base, rod, boss, and clamp
metre rule

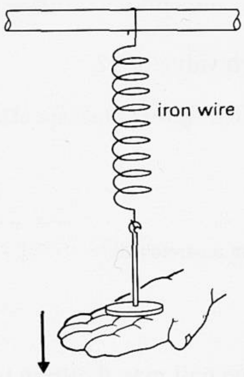


Figure A73

Wind the iron wire around the former to produce a closely wound 'spring' with a suitable hook at either end. Suspend it from a clamp and attach 0.1 kg to the lower end, supporting the mass so that the 'spring' is unstretched. Release the mass and measure the extension. Calculate the potential energy lost by the mass.

Did the mass oscillate before coming to rest?

Rewind the coil to its original shape and plot a force–extension graph by loading it with small masses up to about 0.2 kg. Compare the area under the graph up to the extension caused by the original 0.1 kg, with the potential energy lost by that mass. How close you would expect the two values to be? Justify your answer.

How is this experiment relevant to real devices such as climbing ropes and car safety belts, or to situations where energy is absorbed by crash barriers and car bodies?

EXPERIMENT/DEMONSTRATION
A13 An optical analogue of X-ray diffraction

either
m.e.s. bulb, 2.5 V, 0.3 A, in holder
cell holder with 2 cells
or
lamp, 12 V, 24 W, in holder
transformer
card
pin
colour filters
leads
hand lens

set of Nuffield diffraction grids
and/or
piece of material with regular structure, *e.g.*, cotton handkerchief, or piece of fine mesh nylon, or Terylene net, or umbrella fabric
microscope slide dusted with lycopodium powder

Experiment

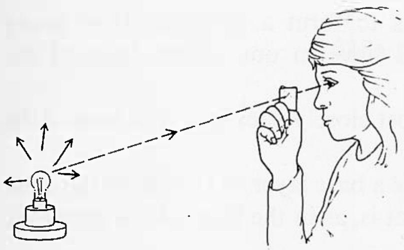


Figure A74

Set up a point light source. Place the material close to your eye and look at the light source.

What happens to the pattern you see if you stretch the material? Rotate it? Tilt it? How is the pattern you see related to the structure and the spacing of the threads? Given a photograph of the pattern, could you have guessed the structure of the object diffracting the light?

Look at the lamp through the glass slide covered in lycopodium powder. How does the pattern you see differ from the pattern made by rotating the handkerchief about the axis of the light beam? (Imagine a time exposure made as the handkerchief is rotated.)

How is the lycopodium powder arranged on the slide?

Repeat the experiment with the Nuffield diffraction grids, if available. Use the hand lens to observe the 'particle' arrangement in each grid and compare with the pattern you see when looking through the grid.

For at least one of the objects you have been looking through, compare the effect seen with red and with blue light. What happens to the pattern you see as the wavelength of the light is decreased?

Demonstration

Compare the width of the diffraction pattern on the screen made by wires of known diameter, with the width of the pattern made by the lycopodium powder. Estimate the size of the powder particles. How would the patterns have been different if a laser emitting blue light had been used?

This experiment is an optical analogue to the X-ray diffraction method used by von Laue to look at the structure of crystals. X-rays used have wavelengths of about 0.1 nm. What, approximately, is the wavelength of the visible light emitted by the laser? Would the pattern have been wider or narrower if a 'laser' emitting X-rays had been used? Would smaller particles give wider or narrower rings?

To produce a pattern with X-rays the same size as was produced with light, what size particles would have to be used? How does this compare with the size of an atom?

Suggest two reasons why X-ray diffraction photographs of real materials will be more complex than the diffraction patterns from the simple regular (or completely irregular) single sheets you have used.

DEMONSTRATION/EXPERIMENT

A14 How atoms are arranged in metals

either
40 expanded polystyrene spheres, 50 mm diameter (demonstration)
or
40 glass marbles or other small spheres (experiment)

4 books (or wooden battens 0.25 m long)

A

Put 20 balls within the battens to form a 5 × 4 ball rectangle. How many nearest neighbours does each ball have?

Add three more layers of balls to form a pyramid. How many nearest neighbours does each ball have in one of the faces of the pyramid?

In which planes are the balls most closely packed — the base of the pyramid or its faces?

Use a triangle of battens to make a base layer of 15 balls in the close packed hexagonal arrangement (that is, as in the faces of the pyramid). Add further layers.

The model you have built represents a common crystal structure for metals, in which the atoms are packed together as closely as possible. How many nearest neighbours does an atom in the middle of one of these structures have?

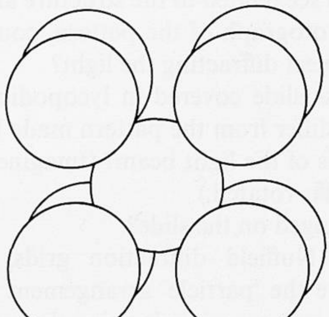


Figure A75
Part of a body-centred cubic crystal structure.

In another possible structure for metals the layers of atoms are arranged in more open square arrays. Those in the first and third layers are at the corners of a cube, which has an atom from the second layer at its centre (figure A75). How many nearest neighbours does each have in this arrangement?

DEMONSTRATION

A15 An intermolecular force model using a linear air track

air track and accessories
air blower
elastic cord
2 small magnets to be attached to vehicles

Two identical air track vehicles represent two molecules interacting with each other. They are connected by an elastic cord and each vehicle has a magnet attached repelling its neighbour. What force does the elastic cord represent? What force do the magnets represent?

How does the force of attraction vary for two molecules as they move apart? How does the force in the cord vary as the vehicles move apart?

Another model could be constructed where the magnets attract and springy buffers replace the elastic cord. Would this be a better model for the intermolecular force? Explain.

What does the oscillating situation represent?

At what position does the system have minimum potential energy? The potential energy is nearly zero when the vehicles (molecules) are at large distances as the attracting force is very small. When the separation is less than the equilibrium distance you have to apply more and more force to push the vehicles (molecules) closer and closer together. Relate the main features of the potential energy–separation curve to those of the force–separation curve.

EXPERIMENT/DEMONSTRATION

A16 Chain molecules, dislocations, and alloys

A16a Splitting of stretched rubber/polythene

2 squares of balloon rubber, 50 mm × 50 mm
pin
polythene strip, 100 mm × 10 mm, 250 gauge (about 0.05 mm, *e.g.*, from a food bag)

Hold a piece of rubber and 'stir' the middle with a pin to pierce it. Now stretch the second piece of rubber and 'stir' near one corner with the pin. Now stretch the rubber at right angles to the first direction, and 'stir' in another corner.

How does the piercing and the hole change when the rubber is stretched? Can you explain this in terms of the molecular structure in rubber?

Split a strip of stretched polythene. Is the effect the same as with the rubber?

A

A16b Bubble raft model: dislocations, grain boundaries, and foreign atoms

Petri dish
length of rubber tubing to fit gas tap
hypodermic needle, 25 gauge
2 L-shaped pieces of wire, about 2 mm diameter and 10 cm long
bubble solution
Hoffman clip
Bunsen burner

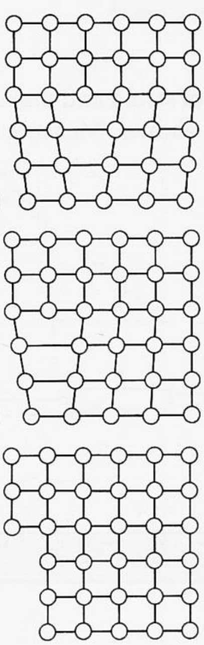


Figure A76
Movement of a dislocation.

Practise making bubbles one to two millimetres in diameter in the dish. Use the Hoffman clip and alter the depth of the needle in the solution for fine adjustment. Passing the Bunsen burner quickly across the surface will clear it for another attempt.

Make a raft of identical bubbles. How many bubbles surround each single bubble? Of which crystal structure(s) is the raft a two-dimensional model?

Make a bubble raft large enough to squeeze between the pieces of wire. Observe the movement of grain boundaries.

Look for dislocations running along a row of bubbles as the raft is deformed. Does this form of slipping happen more easily than the slipping of whole layers together? Explain the analogy: to adjust the position of a carpet, it helps to form a ruck and kick it across the carpet, thus moving the carpet a few centimetres. To pull the carpet the same distance bodily is very hard.

Make more dislocations by bursting some bubbles with a hot wire. Does it become easier or harder to compress or stretch the raft?

Make a raft which includes a few larger bubbles (foreign atoms). How do these affect the movement of dislocations?

Why do small soap bubbles act as good models of a two-dimensional crystal? Think of the attractive and repulsive forces between atoms. What forces act between soap bubbles?

A16c Heat treatment of steel

either
4 steel sewing needles
or
5 cm wire from expendable steel spring

2 pairs of pliers
Bunsen burner
safety spectacles

Safety note: Wear eye protection.

A steel sewing needle will bend before it snaps. Its properties are changed by heating depending on how the alloy atoms of carbon are distributed in the iron. If the needle is cooled slowly after heating it can be bent easily. If quenched (cooled rapidly) it is very hard and brittle. If tempered (reheated and cooled slowly) it becomes ductile again, is fairly hard and much tougher. Tempered steel is a form in common use.

EXPERIMENT
A17 Measuring the forces on systems in equilibrium

2 retort stand bases, rods, bosses, and clamps
2 G-clamps
2 spring balances, 10 N
mass, 1 kg
0.5 m rule or lath
protractor
string

A17a Triangle of forces and resolution

Tie the mass to the centre of a length of string and make a loop at either end. Attach two spring balances as shown. Measure T, F, and θ for various values of θ.

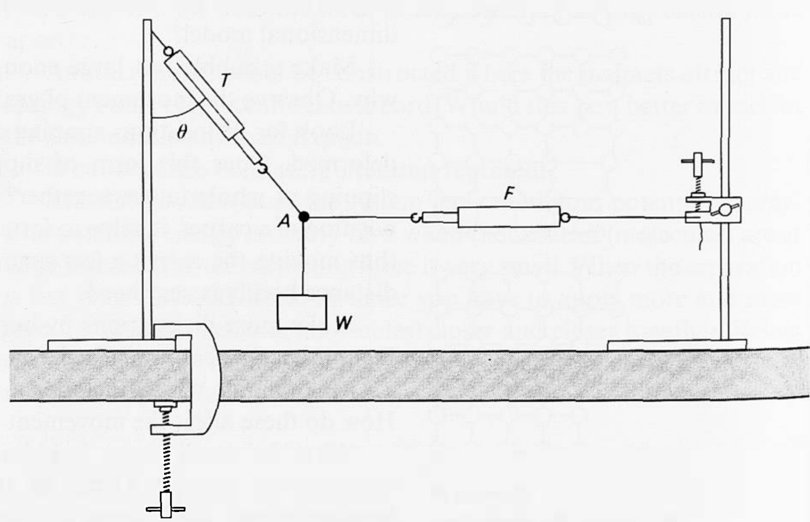


Figure A77

For each set of measurements draw a space diagram of the situation with arrows representing the magnitude and direction of the forces acting at point A. Draw another diagram in which the force vectors are joined head to tail (force diagram) to verify that they form a closed triangle when in equilibrium. Show that the 'closed triangle' condition is equivalent to

$W = T \cos \theta$

and

$F = T \sin \theta$

Show that for small angles θ, F is proportional to the horizontal displacement of the weight W.

A

A17b Strut or tie?

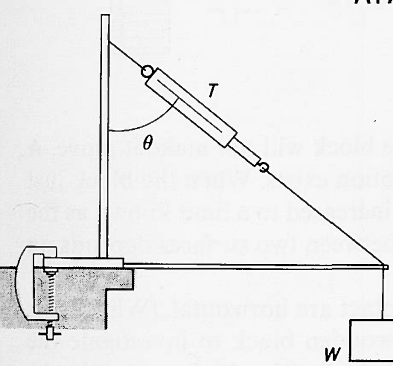


Figure A78

Clamp the retort stand close to the edge of the bench so that the rule can be pivoted freely at the edge as shown. Tie the mass to the end of the rule, making sure that it cannot slip. Connect a string and spring balance between the end of the rule and the retort stand. Measure the tension in the string when the rule is horizontal.

What is the magnitude and direction of the force in the rule? Is this situation identical to experiment A17a, replacing F by the rule? If not, how is it different?

For three non-parallel forces to be in equilibrium their lines of action must pass through a point. Use this idea to decide which of the arrangements in figure A79 is stable. Then check your predictions by trying to set them up.

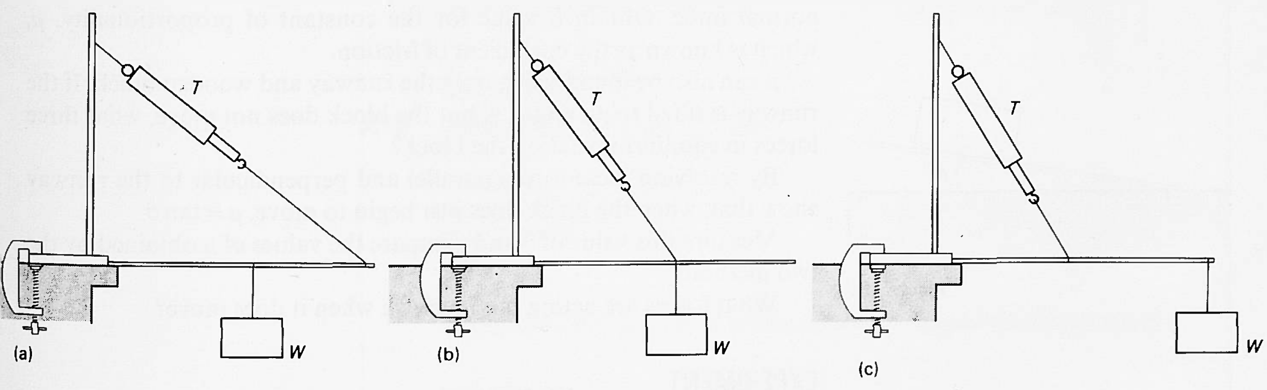


Figure A79

Why is arrangement (a) stable? What force(s) besides W and T act on the strut? What equilibrium condition is obeyed by this arrangement?

Do any of the sketches show unstable situations? What would have to be done to make them stable? What equilibrium condition could then be satisfied?

A17c Determination of the coefficient of static friction for two wooden surfaces

trolley runway
wooden block with screw eye
several 1 kg masses
hanger and slotted masses, 0.1 kg
single pulley on clamp
string

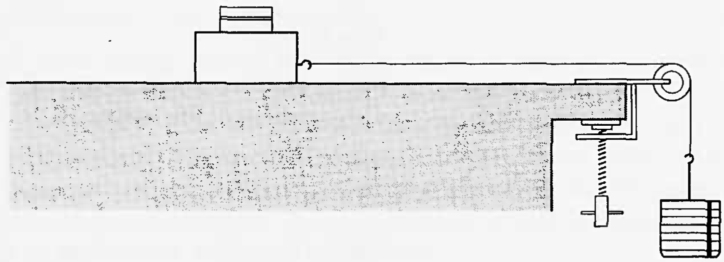


Figure A80

A small horizontal force applied to the block will not make it move. A frictional force sufficient to prevent motion exists. When the block just begins to move the frictional force has increased to a limit known as the limiting friction. The limiting friction between two surfaces depends on the normal force between them.

Ensure that the two surfaces in contact are horizontal. (Why is this necessary?) Increase the load on the wooden block to investigate the relationship between normal force and the limiting friction (that is, the *minimum force required* to move the block).

You should find that the limiting friction is proportional to the normal force. Obtain a value for the constant of proportionality, μ, which is known as the coefficient of friction.

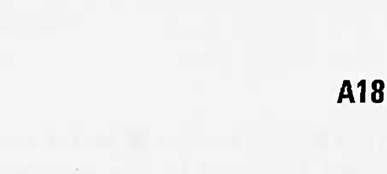


Figure A81

μ can also be found using only the runway and wooden block. If the runway is tilted to an angle, θ, but the block does not move, what three forces in equilibrium act on the block?

By resolving these forces parallel and perpendicular to the runway show that, when the block does just begin to move, $\mu = \tan\theta$.

Measure this value of θ and compare the values of μ obtained by the two methods.

What forces are acting on the block when it does move?

EXPERIMENT

A18 *Investigating the forces at the supports of a loaded bridge*

2 spring balances, 10 N
2 retort stand bases, rods, bosses, and clamps
metre rule
2 hangers and slotted masses, 0.1 kg
string

Use the spring balances (as supports) to hang the rule (bridge) horizontally from the two clamps. The rule should have its faces vertical. The supports need not be at the very ends of the bridge.

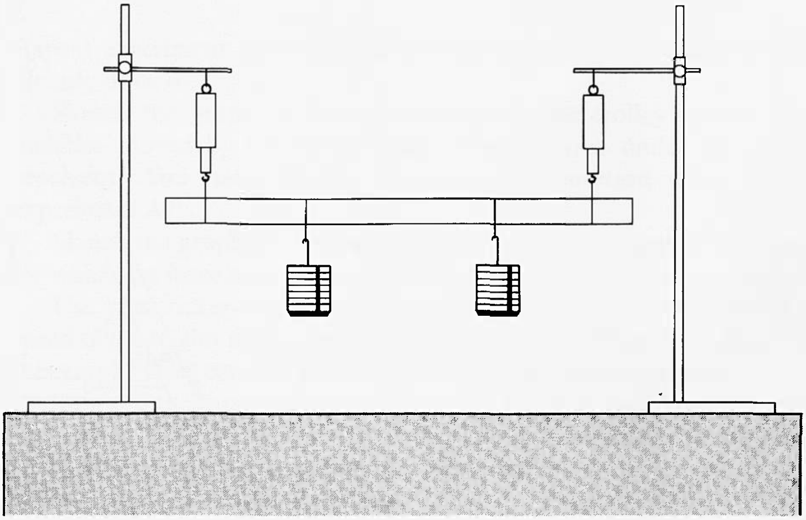


Figure A82

Hang masses from the bridge placed a suitable distance apart to act as the loads of the front and rear axles of a lorry crossing the bridge.

Investigate the way in which the forces on the bridge supports change as the lorry moves across.

How is the model over-simplified? For example, consider the weight of the lorry compared with that of the bridge, the areas over which the load is distributed, the rigidity of the bridge structure, etc.

EXPERIMENT
A19 'Weighing' a retort stand

2 retort stand bases and rods
boss and clamp
mass, 0.5 kg (or 1 kg)
string

Using only the apparatus given, find the mass of the retort stand.

EXPERIMENT
A20 Investigating the forces in a roof truss

2 dynamics trolleys
Plasticine
2 laths about 0.5 m long (or 0.5 m rules) with holes at 5 cm intervals
mass, 1 kg
spring balance, 10 N
bolt with nuts and washers (about 40 mm long, 5 mm diameter)
string

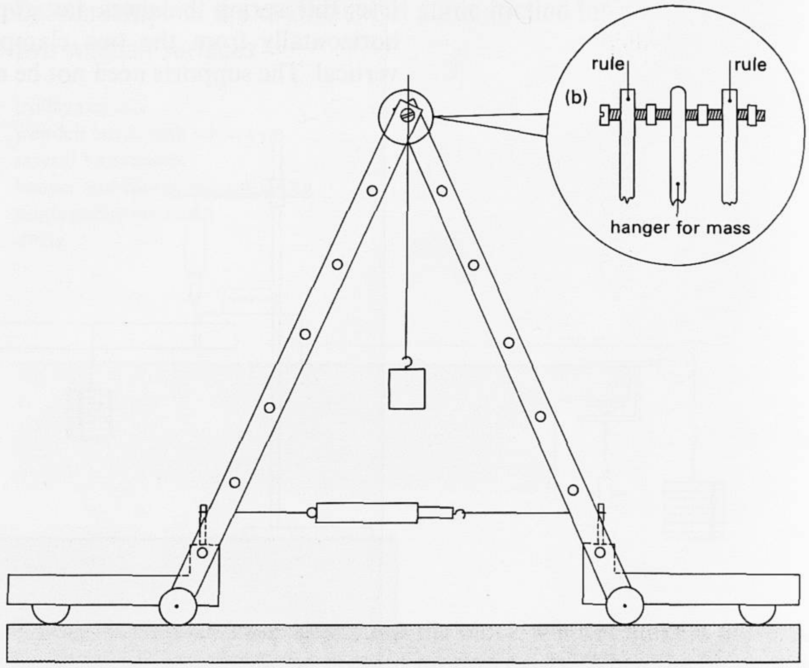


Figure A83

Bolt the two rules together as shown in figure A83, so that they can pivot freely and there is space between to hang the 1 kg mass. The screw which fixes a trolley wheel to the trolley's body passes through a hole in the lower end of each rule. The rules should pivot freely at each end. Attach the spring balance to the two dynamics trolleys. Measure the force in the 'tie bar' and at the apex angle. You may need to steady the apex to prevent the structure toppling sideways.

Are the struts in tension or compression?

Draw space and force diagrams for each corner of the structure to find the force in each strut and the normal force on each trolley.

Suppose the tie bar were made longer, so that the 'roof' was less steeply pitched. Would the forces in the struts change? Lengthen the tie bar with a piece of string and check your prediction.

If the tie bar was placed across the mid points of the two rules, what would you expect the force in it to be (assuming the apex angle to remain unchanged)?

The walls of a house are not mounted on trolleys. Why in this experiment were the struts on trolleys? What extra force(s) would be acting if the struts had been placed directly on the bench top? Would the tension in the tie be greater, smaller, or the same? The walls of a house are rather firmly attached to the ground: what effect does this have on the tension in the roof joists?

EXPERIMENT
A21 Measurement of momentum change and impulse

Apparatus as for experiment A9b(*ii*)

Repeat experiment A9b to make a single ticker-tape if you have not already done so.

Sketch the graph of the force acting on the trolley against the distance moved by this force. What does the area under the curve represent? You have already answered this question when doing experiment A9b.

Sketch the graph of the force acting on the trolley against the time for which the force acts. What does the area under this curve represent?

Use your ticker-tape to plot a graph of v against t, where v is the speed of the trolley after a time t, starting from rest. What is the slope of this graph? How can this graph be related to the force–time one?

Suppose the force acting on the trolley had not been constant but had varied. Why would you still expect the area under the force–time curve to represent the same quantity as before?

A

DEMONSTRATION
A22 Collisions on an air track

air track and accessories
air blower
2 photodiode assemblies and light sources
card
2 timers, resolution 1 ms

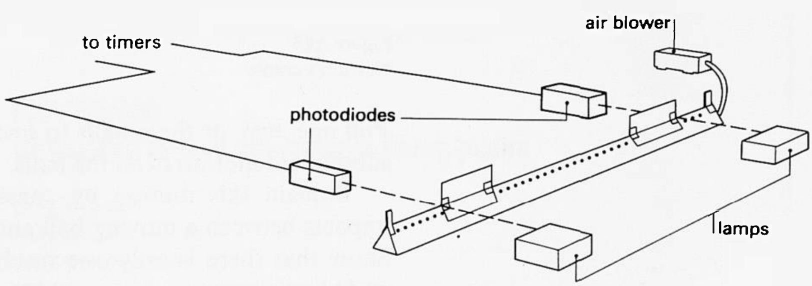


Figure A84
Collisions on an air track.

The track and vehicles need to be kept clean, and vehicles should be stored and handled in such a way that they do not become deformed.

Use one vehicle first on the air track to check that it is level.

Vehicles can be fitted with nose-pieces, for example elastic bands, magnets, needles, corks, Plasticine, etc., so that elastic or inelastic collisions can be achieved. Any load on a vehicle must be balanced, or it will lift at the less loaded end and be driven along by air from the track.

Vehicles of the same or different masses can be used with one vehicle stationary, or both moving, for both elastic and inelastic collisions. A maximum of four separate times must be measured to calculate the speeds of the vehicles before and after collision. An explosive separation can also be investigated by compressing a spring between the two vehicles and then releasing them.

Calculate the momentum, mv, and the kinetic energy, $\frac{1}{2}mv^2$, of each vehicle before and after the collision.

Find the change in the total mv and in the total $\frac{1}{2}mv^2$ of the two vehicles caused by the interaction.

Is the total momentum of the vehicles conserved to within the uncertainty of the measurements?

When is the total kinetic energy conserved? What becomes of it when it is not conserved?

DEMONSTRATION

A23 Newton's cradle: investigation of a line of colliding balls

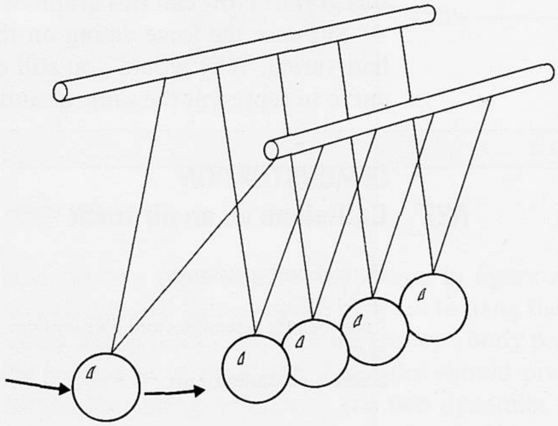


Figure A85
Newton's cradle.

Pull one, two, or three balls to one side and release them. Observe the subsequent motion of all the balls.

Explain this motion by considering a series of separate elastic impacts between a moving ball and a stationary one of the same mass. Show that there is only one result which conserves both momentum and kinetic energy.

Why is it important that the centres of the balls should lie in a horizontal line? Why should the balls just touch? What will happen if either of these conditions is not fulfilled?

What would happen if three or four of the balls were stuck together?

What would happen if the middle ball was much denser but of the same size as the others?

Why is it necessary to suspend the balls on a bifilar suspension? Why not roll marbles along a narrow track?

DEMONSTRATION

A24 Measurement of the speed of an air rifle pellet using a ballistic pendulum

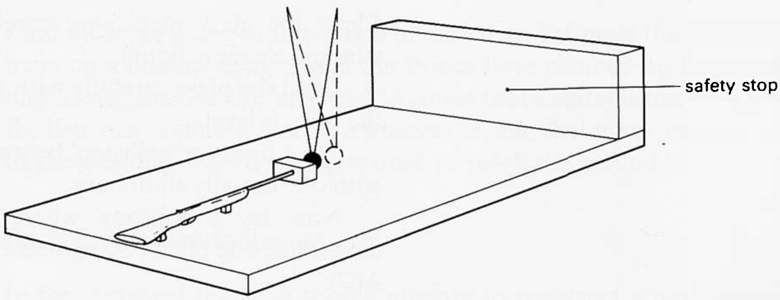


Figure A86
Measuring the speed of an air rifle pellet.

Any pellet which misses, or passes through the Plasticine, must enter some soft, absorbing material.

The apparatus is set up so that the Plasticine bob hangs in front of the muzzle of the air rifle and about 2 cm from it. The pellet is fired into the Plasticine and the maximum height through which the bob rises is measured.

Use the Law of Conservation of Energy (that is, initial kinetic energy transformed into gravitational potential energy) to calculate the initial speed of the Plasticine bob.

Use the Law of Conservation of Linear Momentum to find the speed of the pellet in terms of the masses of pellet and bob and the speed of the bob. Hence calculate the muzzle velocity of the pellet.

Estimate the uncertainty of your result.

EXPERIMENT

A25 Collisions in two dimensions using pucks

CO_2 pucks kit
CO_2 cylinder
dry ice attachment
camera
motor-driven stroboscope
safety spectacles

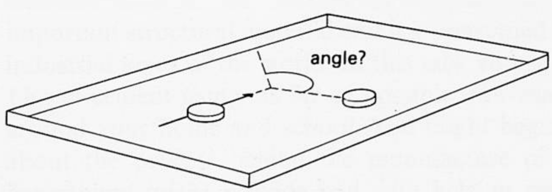


Figure A87
'Collision' between two magnetic pucks.

A

Safety note: Lumps of solid carbon dioxide should always be handled with tongs and/or thick gloves, 'snow' with a spatula or spoon. Eye protection should be worn. Before crushing, lumps should be covered with a cloth.

Clean the glass plate very carefully with methylated spirit and/or window-cleaning liquid.

Level the plate carefully with the wedges. Use a puck to check that the plate is level.

Try a head-on 'collision' between two magnetic pucks of equal mass with one initially stationary.

Now try a collision where both pucks move off in different directions, one puck having been stationary before the collision (figure A87).

Observe the angle between the directions of the two pucks after collision. Does it depend on the direction of the incident puck?

Repeat the experiment with pucks of unequal mass (that is, by adding masses or a second puck on top of the first) and draw some general conclusions about the angles after collision for each case. How are these results applicable to the analysis of cloud chamber photographs where elastic collisions between fast and very slow moving particles occur?

You may be able to take multiflash photographs of these events, and of collisions between two moving pucks. Take measurements from the photographs to test whether momentum is conserved in two dimensions.

HOME EXPERIMENTS

AH1 Saved by a hair!

Find the force required to break a human hair. Estimate the number of hairs on a human head. Could the Prince have climbed up Rapunzel's hair as suggested in the fairy tale? (Assume that a suitable anchorage for the hair was available, such as a window tie, and that magic enables hair to grow rapidly until it is long enough to reach the ground.)

AH2 An accurate newtonmeter

A

In this practical task you should attempt to construct a newtonmeter from a home-made spring that can resolve forces to 0.001 N with a range of 0 to 1 N. Check the accuracy of your mechanism by 'weighing' an object of known mass. Your spring must obviously extend by a measurable amount when the load is applied but you might consider ways of 'amplifying' the extension when measured against the scale of your device. Compare your device and its accuracy with others in the class.

AH3 The jelly column

Use ordinary dessert jelly from the grocers to make two identical columns with a base diameter of 4 to 6 cm. Use concentrations recommended by the manufacturer and arrange matters so that it is easy to remove each column from the mould you have used.

Before one of the moulds has set, mix in a small quantity of some fibrous material such as wool or hair to form a rudimentary 'composite material'. After removing the moulds, compare the columns as you think a scientist might. You might make a qualitative comparison between the elastic properties of the two materials. You might test each column to destruction and closely observe how failure occurs in each. Watch particularly for the way in which cracks are propagated.

Compare your effort with others in the class.

AH4 Cement

Cement, used in the making of mortar and concrete, is a most important structural material and it is consumed in vast amounts in the industrial areas of the world. In this task you should attempt to make 1 kg of cement using, as far as possible, raw materials obtained in or around your home and school. You might begin this task by reading about the process behind the manufacture of cement. The pottery department might provide you with help in processing your cement mixture.

After processing, see if your 'cement' will set after mixing with water and, maybe, sand. Compare your product with others in the class and with ordinary builders' cement.

QUESTIONS

The variety and behaviour of materials

1(I) Imagine that you are blindfolded and a piece of string is put into each of your hands. You are told that the strings are tied to the ends of a specimen which you can stretch. As you start to pull, it hardly extends at all, but when you pull a little harder it starts to stretch very easily and quite rapidly. Then you relax and it contracts again, but not back to its original length.

Sketch a graph to represent these observations.

2(E) The graphs in figure A88 show how the lengths of various materials vary as the force extending them is increased. For each graph, describe the behaviour of the substance. Hazard a guess as to what each might be. Each specimen was originally 100 mm long and the area of cross-section was $1\ mm^2$.

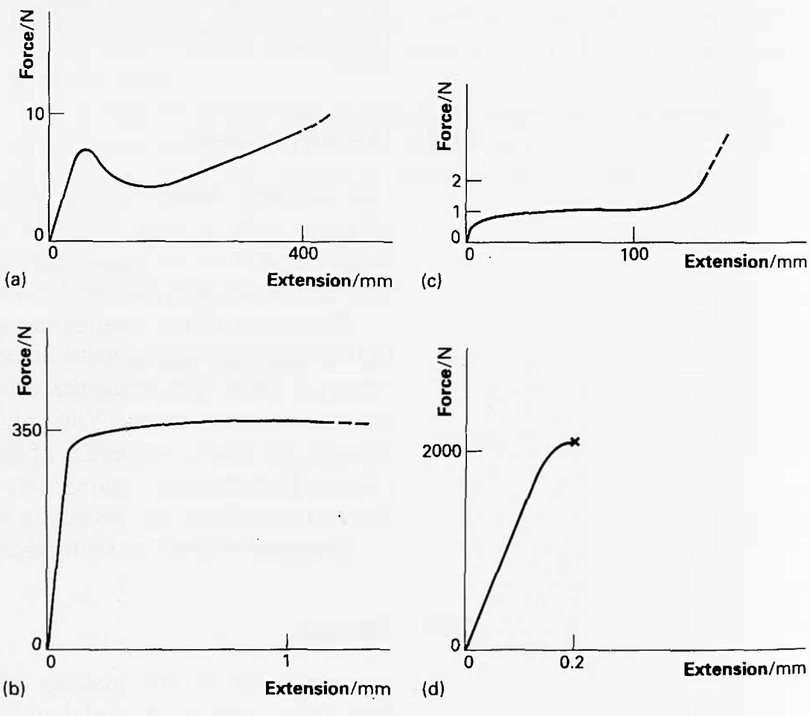
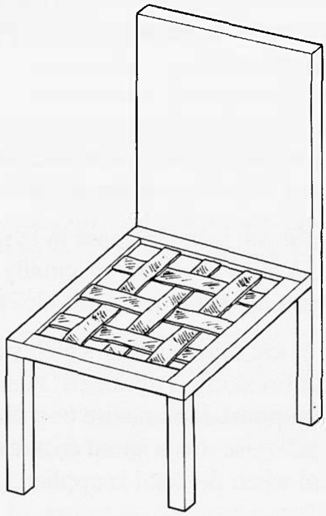


Figure A88

3(L) Read the definitions of the words 'ductile', 'elastic', 'plastic', 'strong', 'tough', and 'brittle' on pages 3 and 4. Using these words, classify the following substances: polythene, rubber, copper wire, brick, lead, Plasticine, cast iron, steel, biscuit, human skin, glass, bone.

4(P) Suppose that the graph (figure A89b) is the load–extension curve for rubber webbing used as the base of a chair.

(a)



(b)

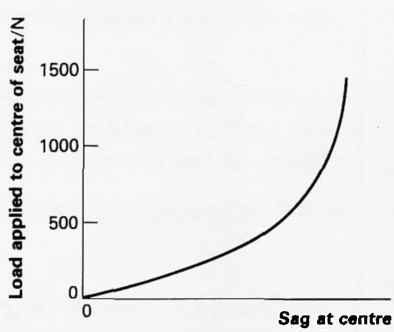


Figure A89

a The following are predictions about what will happen when a person sits on the chair.
i He will sink only a little, unless he is very heavy, when he will suddenly sink a lot.
ii He will sink a moderate distance and then be supported at about the same level whether he is heavy or light.
Explain which is the correct prediction.

(Short answer paper, 1971)

b Describe the motion of a person who 'flops' into the chair.

Stress and strain

5(L) For a steel spring, obeying Hooke's Law, the extension, x, is proportional to the applied force, F, such that

$F = kx$, where k is called the *force constant* of the spring.

a A light vertical spring is extended 10 mm by a load of 1.0 N. What is its force constant?

b A second, identical spring is connected to the end of the first and the same load is hung from the pair. What is the extension? What is the force constant of the pair together?

c The two springs are disconnected and hung side by side from the same support. The ends are connected together to the same load. What is the extension? What is the force constant of the pair together?

d k is a measure of the stiffness of the system. How is the stiffness of the single spring related to the stiffness of the pair in 'series' and in 'parallel'?

e To answer part **b** you have used the fact that the extension per spring is the same for a given stretching force. In part **c** double the force would be required to produce the same extension as for a single spring. How do these experiments illustrate the importance of the quantities *stress* and *strain*?

6(P)a *Tensile stress* is tension per unit area of cross-section. A long strip of rubber whose cross-section measures 12 mm by 0.25 mm is pulled with a force of 3 N. What is the tensile stress in the rubber? Give the units.

b *Tensile strain* is the increase in length as a fraction of the original length. A strip of rubber originally 90 mm long is stretched until it is 120 mm long. What is the tensile strain? Why has the answer no unit?

c The greatest tensile stress which steel of a particular sort can withstand without breaking is about $10^9\ \mathrm{N\,m^{-2}}$. What is the greatest load that can be supported on a wire of cross-sectional area $0.01\ \mathrm{mm^2}$ made of this steel? (Use the original cross-section in calculation, as if it were not reduced when the load is applied.)

d Estimate the diameter of a single steel wire which would suspend a car without breaking.

e A wire 2 m long is given a strain of 0.01. By how much has its length increased?

f Rubber needs a stress of roughly $10^6\ \mathrm{N\,m^{-2}}$ for each unit increase in strain. What is the tension in a rubber band 1 mm thick and 3 mm wide stretched to three times its original length? (The question is ambiguous. Explain why.)

g A student finds that a particular steel wire needs a force of 10^2 N to increase its length by one per cent, and records this as 10^4 N per unit strain. Another student thinks this result means that 10^4 N are needed to double the length of the wire. What is wrong with this interpretation? Is the record sensible in the form given?

7(P)a A specimen of rubber of cross-sectional area $2\ \mathrm{mm^2}$ is extended in length from 0.1 m to 0.15 m by a force of 0.4 N. Use these results to predict the force needed to extend a piece of the same material with $4\ \mathrm{mm^2}$ cross-section from a length of 0.50 m to 0.75 m.

b On the basis of the above data, either calculate exactly or estimate roughly the force needed to stretch the second piece of rubber
i from 0.50 m to 0.55 m
ii from 0.50 m to 3.50 m.
Comment on your answers.

c If a 20 kilogram mass hanging on a steel wire of $1\ \mathrm{mm^2}$ cross-section produces a 0.1 per cent strain in the wire, what mass hanging on the wire would give it a strain of 10 per cent?
Comment on your answer.

8(P)

Material	Young modulus/ $N\,m^{-2}$
cast iron	15×10^{10}
mild steel	21×10^{10}
wood, spruce:	
along grain	$1.0\text{–}1.6 \times 10^{10}$
across grain	$0.04\text{–}0.09 \times 10^{10}$
glass	8×10^{10}
Perspex	0.6×10^{10}

Table A1

a The Young modulus for glass is higher than that for Perspex. What does this tell you about the ease of stretching glass compared with Perspex? Which material is stiffer?

b The Young modulus for wood is different along the grain compared with across the grain. How does this show up when you flex a thin sheet of wood along the grain direction and then across the grain?

c Wood has a much lower value of Young modulus than steel. Which would be the easier to stretch?

9(E) In Arthur C. Clarke's novel *The fountains of paradise*, a material is developed which is so strong that, when in the form of a thread so fine as to be invisible unless looked for very carefully, it will support the weight of a human.

a Estimate the minimum breaking stress of this material.

b Compare this with the breaking stress of steel, about $1 \times 10^9\,N\,m^{-2}$.

c For an engineer *yield stress* is as important a quantity as breaking stress. It is the stress at which permanent or plastic deformation starts. For safety reasons any wire, beam, or strut in a system must withstand four times the maximum stress for which it is designed. The yield stress for steel is about $3 \times 10^8\,N\,m^{-2}$. What diameter steel wire is needed to hoist a person safely?

Dimensions

10(L) The dimensions of a physical quantity are found in terms of [mass] = M, [length] = L, and [time] = T. Thus, the dimensions of velocity are $L\,T^{-1}$, written [velocity] = $L\,T^{-1}$. Dimensional analysis is a powerful method of checking whether an algebraic expression is likely to be correct.

a Write down the dimensions of force (remember $F = ma$).

b What are the dimensions of the force constant or stiffness of a spring, k (*i.e.*, from Hooke's Law $F = kx$)?

c What are the dimensions of frequency?

d A student remembers that either the frequency or the period of oscillation of a spring is proportional to $\sqrt{\frac{k}{m}}$. Use a dimensional check to decide which it is.

e The constant of proportionality in part **d** is $1/2\pi$. This is known as a dimensionless constant. Can you suggest why it is so called? In Hooke's Law, k is a constant of proportionality too, but as you have shown it has dimensions.

f What are the dimensions of stress, of strain, and hence of the Young modulus?

g In an experiment to measure the Young modulus for glass, a glass slide acted as a simple cantilever. The theory of the bending of beams relates the Young modulus, E, to the force, F, acting on the cantilever causing a deflection, y, by the expression:

$$E = \frac{4L^3F}{bd^3y}$$

where L is the length, b the width, and d the thickness of the glass slide. Check that the righthand side of the equation has the same dimensions as the Young modulus.

Elastic energy

11(L) Some babies play in a 'bouncer'. This is a harness attached to a rubber cord hung from a door frame, and the baby is suspended so that its feet just brush the floor. Babies do actually seem to enjoy it, although it sounds, and looks, like an elaborate form of torture!

a Suppose a baby has a mass of 10 kg. What is its weight in newtons?

b This weight may stretch the rubber cord by 20 cm (0.2 m). If the force exerted by the cord were proportional to the amount it is stretched, what force would it exert when the baby has been attached to the unstretched rubber cord and then lowered by 2 cm (0.02 m)?

c What is the average force exerted by the rubber as the baby is gently lowered the full 20 cm?

d What is the energy stored in the rubber when the baby has been lowered 20 cm? (Use the average force, and the total distance.)

e If the greatest force exerted is F, and the greatest extension is x, what is the energy stored if the force is proportional to the extension?

f In fact, however, for rubber the proportionality assumption made above is wrong. The graph of force and extension will be as in figure A90. If the force at 20 cm is still 100 newtons, is the energy stored more, or less than that given by the answer to **e**? Explain your reasoning.

($g = 10\,\mathrm{N\,kg^{-1}}$ approximately.)

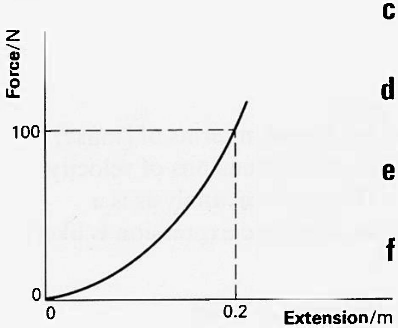


Figure A90

12(P) Figure A91 shows the apparatus with which the stroboscopic photograph (figure A92) was made. The photograph shows the distance scale marked in 0.1 m intervals and below it a series of 'glimpses', at 0.1 s intervals, of the peg attached to the trolley. An elastic cord was held at one end on a fixed peg (whose shadow obscures the righthand mark 2 on the scale) and at the other end by the peg on the trolley. The cord was just taut when the trolley peg was at the zero mark on the scale. Then the trolley was pulled back so that its peg was below the lefthand mark 5, that is, half a metre extension of the elastic. At this point the cord pulled the trolley with a force of 0.44 N. The mass of the trolley was 1.0 kg. The trolley was then released from rest, starting from the mark 5 of the scale. As the trolley peg passed the zero mark, the cord became slack and dropped off the fixed peg.

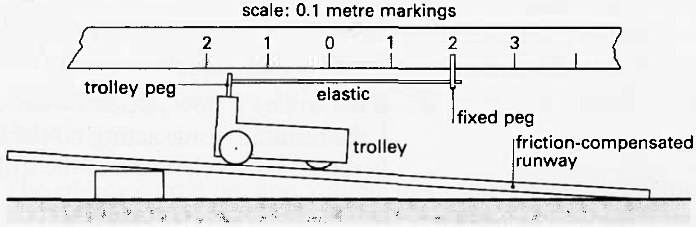


Figure A91

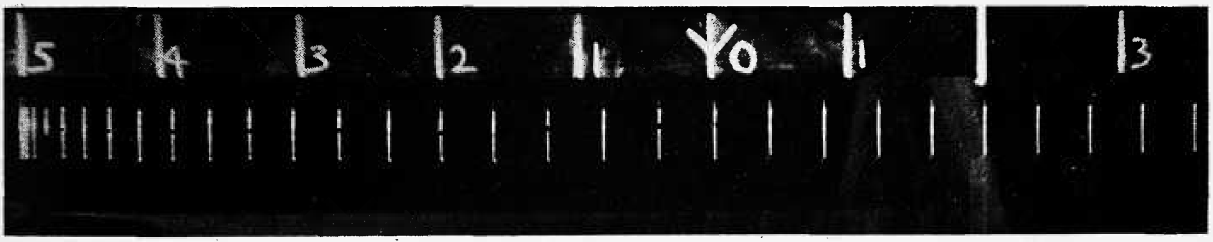


Figure A92

a From mark 5 to mark 0 the trolley accelerates. Would you expect uniform acceleration?

b Calculate the speed of the trolley after the cord has stopped pulling and hence its kinetic energy.

c How much energy would have been stored in the elastic cord had the force been proportional to the extension?

d Compare the answers to **b** and **c**. Is the supposition made in **c** likely for a rubber cord? How might the comparison of **b** and **c** be explained?

e Find the kinetic energy of the trolley at a number of different distances to the left of the zero mark; that is, for several different extensions of the rubber. (Find the kinetic energy from the speed close to that distance.)

Now find the elastic potential energy at each point. For this, you can use the fact that the total energy is constant, and is equal to the kinetic energy after the cord goes slack, since there is then no elastic potential energy. At all points, the total energy is the sum of potential and kinetic energy. Draw a graph of elastic potential energy against extension of the cord.

f Has the curve of elastic potential energy against extension roughly the shape you might expect?

13(R) A trolley of mass 0.80 kg is held in equilibrium between two fixed supports by identical springs (S_1 and S_2) as shown in figure A93(a); each spring has an extension of 0.10 m. In figure A93(b) the trolley is shown moved to the right a distance 0.05 m.

The relation between force F in newtons and the extension x in metres for *each* spring is given by

$F = 20x.$

a What is the *change* in force exerted by spring S_1 caused by moving the trolley to the right as in figure A93(b)?

b If the trolley is now released what will be the magnitude of
i the resultant force acting on the trolley at the moment of release, and
ii the initial acceleration of the trolley?

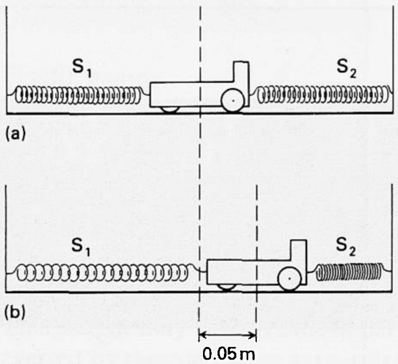


Figure A93

c Showing the steps in your calculations, determine the total energy stored in S_1 and S_2 when the springs are stretched
i as in figure A93(a), and
ii as in figure A93(b).

d What is the kinetic energy of the trolley as it passes through the equilibrium position?

(Short answer paper, 1981)

14(L) The energy stored in a rod of cross-sectional area A, stretched by a length x, less than its elastic limit, is given by $\frac{1}{2}Fx$ where F is the force to produce the extension x.

a What is the tensile stress in the rod under these conditions?

b The rod's original length is l. What is the tensile strain?

c Substitute for F and x in the formula for energy to obtain an expression for the energy stored per unit volume in terms of stress and strain.

d Typical working stresses and strains are given for four different substances in table A2.

	Strain/ %	Stress/ $N\,m^{-2}$
steel	0.3	700×10^6
wood (yew)	0.9	120×10^6
tendon (in ankle)	8.0	70×10^6
rubber	300	7×10^6

Table A2

Which material stores the greatest energy per unit volume, in these typical working conditions?

e The energy stored per unit volume for each of these substances is large compared with that for many other materials. Suggest a situation for each one where this is put to use.

15(E) This question shows why it is a wise precaution to wear safety spectacles when doing experiments to stretch elastic materials until they break.

When a steel wire breaks, about 25 % of the stored elastic energy is transformed to kinetic energy. Show that the speed, v, of the wire when it breaks is given by $(E_p/2\rho)^{\frac{1}{2}}$, where ρ is the density of steel and E_p is the energy stored per unit volume (see question **16**). Use the data from question **14** and $\rho = 8 \times 10^3\,\mathrm{kg\,m^{-3}}$ to estimate the speed of the end of the wire.

16(P) The energy stored per unit volume of a solid which obeys Hooke's Law is $\frac{1}{2}$(stress × strain). Check that this formula is dimensionally correct. Note that the method of dimensions cannot prove that any relationship *is* correct, only that it is possible. Note also that the method gives no information about the numerical constants in a relationship.

17(R) Figure A94 shows a load–extension graph for a length of steel wire.

a Use the graph to estimate:
i how much energy could be stored in the wire and also recovered from it, and
ii the extra energy which would have to be supplied to fracture the wire.

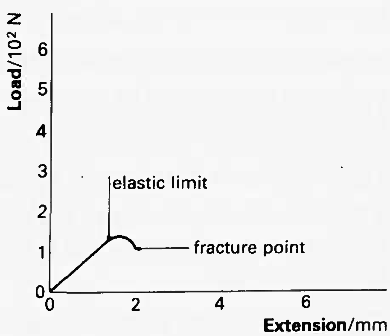


Figure A94

b Copy the diagram and draw carefully on it, the graph as it would have been
i if the wire had been twice as long (label it A), and
ii if instead the wire had had three times the cross-sectional area (label it B).

c Why are very long cables used for towing oil platforms out at sea?

(Short answer paper, 1979)

A

Atoms and molecules

18(L) A spherical oil drop of diameter d spreads out to form a circular patch of radius R on a clean water surface.

a Show that the thickness, h, of the oil is $d^3/6R^2$.

b In an experiment, the following measurements were made:
i $d = 0.5 \pm 0.05$ mm by holding the drop on a cotton thread against a scale and viewing with a hand lens.
ii $R = 9.3 \pm 0.1$ cm using a ruler.
Find the value of h.

c Calculate the percentage uncertainties in d and R and hence find the uncertainty in h.

d Why is the value of h found in part **b** only the upper limit to the length of a molecule?

e Other experiments indicate that the diameter of a single atom is about 2×10^{-10} m. About how many atoms long is an oil molecule?

f Estimate how many atoms there are in the drop on the cotton thread in part **b**.
(The area of a circle, radius R, is πR^2; the volume of a sphere, radius r, is $\frac{4}{3}\pi r^3$.)

19(P) Light of wavelength 600 nm diffracted by lycopodium particles of diameter 30 μm causes a pattern of fuzzy rings on a screen placed at some distance beyond the powder sample along the axis of the beam.

a If X-rays of wavelength 0.1 nm are diffracted at the same angle from a glass sample, what is the ratio of the size of the powder particles to the glass molecules?

b Estimate the size of the glass molecules.

c In another X-ray experiment with a different material the diffraction angle was larger. Are the molecules of the second sample larger or smaller than glass molecules?

20(L) The *mole* is a convenient unit for measuring the quantity of matter when considering atomic or molecular properties. The Avogadro constant, L, is approximately 6×10^{23} items per mole. (More precisely, 6.022×10^{23} mol^{-1}.)

a Use a book of data to find the *molar mass* (the mass of one mole) of sodium atoms and of chlorine atoms.

b What is the molar mass of NaCl?

c How many pairs of Na^+ and Cl^- ions are there in 0.0585 kg of sodium chloride?

d If one mole of sodium atoms and one mole of chlorine atoms combine to form NaCl, one mole of electrons is transferred from sodium atoms to chlorine atoms. How much electric charge is carried by a mole of electrons? (Charge on one electron $= 1.6 \times 10^{-19}$ C.)

e Estimate the volume of a mole of salt.

21(L) Estimate the number of atoms in 1 cm^3 of copper by the following method:

a The molar mass of copper is 0.064 kg mol^{-1}. How many atoms are there in 1 kg of copper?

b The density of copper is 8900 kg m^{-3}. How many atoms are there in 1 m^3 of copper? How many atoms in 1 cm^3?

c If all the atoms stacked neatly as tiny cubes, what would be the 'volume' of a copper atom? Estimate the 'diameter' of a copper atom.

d Gold is one of the densest metals and aluminium one of the least dense. Find the molar volume (the volume of one mole of substance) of gold and of aluminium atoms. (Use tables to find the molar mass and density of each metal.) What conclusion can you draw about the sizes of the metal atoms?

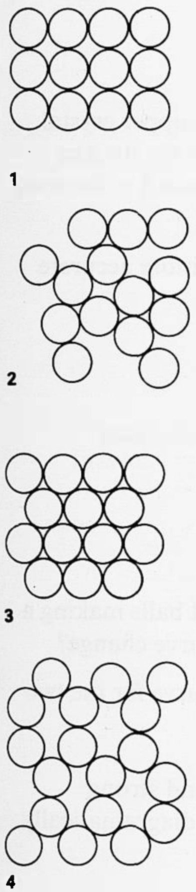


Figure A95

22(E)a Estimate the mass of a single grain of salt. What would be the mass of a mole of grains of salt?

b Write the letter 'O' with a carbon pencil. Estimate how many million atoms have been rubbed from the pencil onto the paper.

c Maximum wear of a car tyre occurs when the car corners or brakes. Assuming that, on average, a layer one molecule thick is worn away per revolution of each wheel, estimate how far the car will travel before each tyre loses a mole of rubber molecules. A rubber molecule is about 10^{-9} m across.

23(I)a Which of the diagrams in figure A95 represents a layer of soap bubbles?

b Explain why soap bubbles take up this pattern.

c Since layers like the soap bubble layer occur in many metals, for example copper, what might be concluded about the forces between the atoms in such metals? (Think about their directions.)

d The ions in an NaCl crystal take up an arrangement rather like **1**. Suggest why this might be.

24(L) The Avogadro constant can be found from knowledge of the size of atoms and how they are arranged in crystals. The molar mass of copper is 0.0636 kg mol^{-1}. The density of copper is 8930 kg m^{-3}.

a Calculate the molar volume, that is, the volume occupied by one mole of copper atoms.

Experimental work with X-rays shows that copper atoms have a *diameter* of 2.55×10^{-10} m. To estimate the Avogadro constant we need to work out the volume effectively occupied by a single copper atom.

b *i* Calculate the volume occupied by a spherical copper atom.
ii Use this value for the volume and your answer to **a** to estimate the Avogadro constant, L, the number of atoms in one mole.
iii Comment on this estimate.

In a real solid there is some empty space between atoms.

c Assume that atoms are arranged in a 'square' array and that each one occupies the volume of a cube, side 2.55×10^{-10} m.
i Calculate the volume occupied by each copper atom on this assumption.
ii Use this value to estimate L.
iii Comment on your answer.

In fact we know from X-ray work that the atoms in a copper crystal are arranged in hexagonal layers, and that these layers are stacked together as closely as possible. In this arrangement about $\frac{1}{4}$ of the total volume is empty space between the spherical atoms.

d Use this information and your answer to **b** to make a more accurate estimate of L.

Intermolecular forces

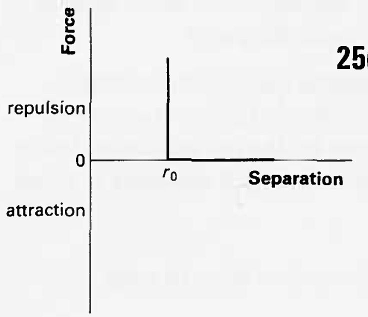


Figure A96

25(I) Figure A96 shows the force–separation curve for two identical perfectly hard spheres.

a Explain the shape of the curve.

b What is the significance of the distance r_0?

c If the theoretical spheres were replaced by two billiard balls making a line of centres collision, how would the shape of the curve change?

d Sketch the shape of the *potential* energy–separation curve for the two billiard balls as they collide.

26(L) Two identical air track vehicles have springy buffers and strong attracting magnets mounted on facing ends as shown diagramatically in figure A97.

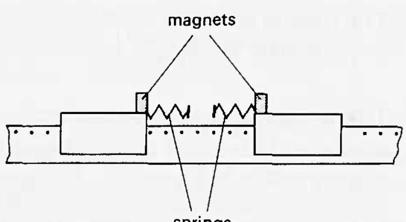


Figure A97

a Imagine that the buffers are removed, and sketch a curve to represent the force–separation graph between the vehicles.

b Now imagine that the springy buffers are replaced, and the magnets are removed. On the same axes sketch a curve to represent the force–separation graph between the vehicles.

c Add the two curves together to indicate the force–separation curve when both attractive and repulsive forces are present.

The force–separation graph for two molecules has the shape shown in figure A98.

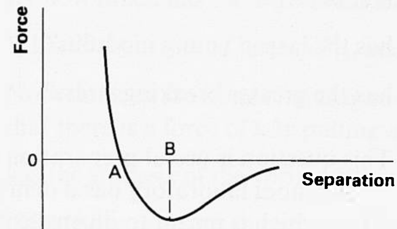


Figure A98

d Does the curve you have sketched for the air track model have a similar shape?

Explain the shape of the curve and the importance of the two separations 0A and 0B.

e Suggest a suitable value for 0A in figure A98.

27(P) The potential energy–separation graph for two atoms is shown in figure A99.

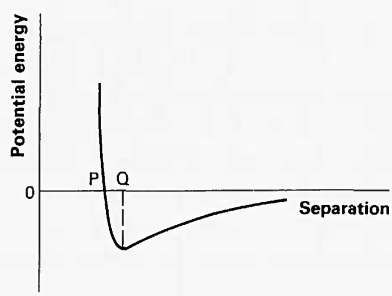


Figure A99

a Explain the shape of the curve and the importance of the two separations 0P and 0Q.

b Using the same separation axis draw figure A99 and figure A98 on the same graph to indicate how the important features of each curve are related to each other.

c The two atoms are not at rest but will have kinetic (thermal) energy and so will oscillate about their equilibrium position. How will the potential energy vary? (Use the figure in your answer.)

d If enough energy is given to the two atoms, they can break free of each other's attractive force (the binding energy). How can the binding energy be found from the graph?

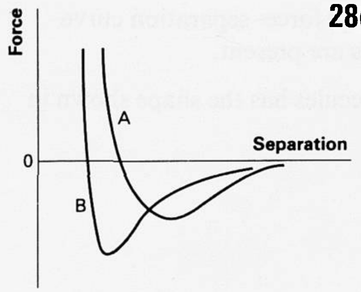


Figure A100

28(R) Figure A100 shows the force–separation curves for a pair of atoms of two crystalline solids A and B. Both solids have the same structure. Which solid

a has larger atoms?

b is stiffer?

c has the larger Young modulus?

d has the greater breaking stress?

29(P) This question is useful preparation for the ideas of the next one.

A school laboratory has a demonstration model, shown in figure A101, which is meant to illustrate the stretching of bonds between atoms as a piece of material is stretched. The model has four horizontal planes of small balls linked horizontally by rods and vertically by springs. There are six balls in each horizontal layer. All the springs are identical and may be taken to be 50 mm long. The dimensions are shown, all in millimetres. When a vertical stretching force of 12 N is applied, the length of 150 mm increases to 165 mm.

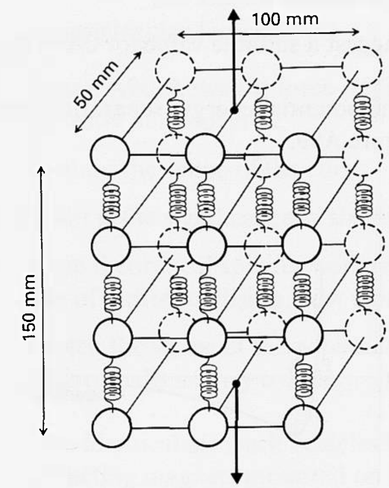


Figure A101

a What is the restoring force for 10 per cent strain for a single spring?

b What is the force constant (restoring force for unit displacement) for a single spring?

30(L) This question makes a link between the Young modulus of a metal (stress/strain), and the springiness of bonds between atoms.

Imagine layers of atoms in square array, each atom distance r_0 from its nearest neighbours both in its own layer and in layers above or below, as shown in figure A102.

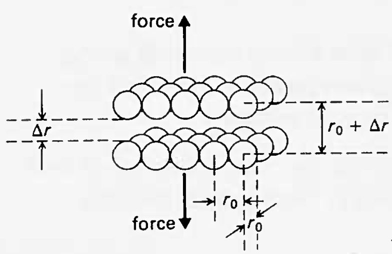


Figure A102

Suppose a long wire, with many layers, is stretched a little so that each layer is now $r_0 + \Delta r$ from those above or below it.

a If there are n layers in the length of the wire, how long is the wire before it is stretched?

b By how much has the wire extended?

c What is the *strain* in terms of r_0 and Δr?

Now think of the bonds holding each atom as being like a spring, so that there is a force of $k\Delta r$ pulling a pair of atoms together.

d k is the stiffness of the spring. What are its units?

e If there are m atoms in each layer, what is the force pulling adjacent layers together?

f The stress is the force per unit area. In terms of the spacing r_0, how many atoms are there per square metre of a layer?

g What is the stress in terms of k, Δr, and r_0?

h What is the elastic modulus in terms of k, r_0?

i For steel, the elastic modulus is 20×10^{10} newtons per square metre. The spacing r_0 is about 3×10^{-10} metre. What is the stiffness, k, of the springy bond?

Non-metallic materials

31(L) This question is about rubber, but it uses an idea from the kinetic theory of gases.

A gas molecule bouncing about from collision to collision in steps of length x will not usually be a distance nx from its starting point after making n steps, for that would need all the steps to be in a straight line. It turns out that the most probable distance is about $x\sqrt{n}$.

A rubber molecule is a long chain of n links, with the links free to swivel so that the chain points hither and thither along its length.

a If each link is of length x, how far will one end of the chain be from the other, on average?

b How long can the chain possibly be, fully stretched out?

c If $n = 100$, at what strain will rubber become very hard to pull out any further?

32(E) This question is about using words well enough to be understood in discussion.

A 'Now let's get this clear. You say that this grain of NaCl here is a little block of one crystal.'
B 'Yes.'
A 'And this piece of copper wire is also crystalline.'
B 'Yes, but it's polycrystalline.'

A

A 'Ah, so there is crystalline and polycrystalline. Is rubber polycrystalline?'
B 'No. Rubber is amorphous until you stretch it.'
A 'Amorphous–you mean like a liquid?'
B 'Yes.'
A 'A liquid doesn't become crystalline when you stretch it?'
B 'Perhaps we'd better go back to the beginning.'

Can you help B?

33(E)a A metal is a crystalline substance, so is sugar. Metal bends, does sugar?

b When sugar is made into toffee it behaves like glass. Glass shatters, does toffee?

c How do you distinguish a glass-like substance from a crystalline substance?

d Why are some crystalline substances ductile and others not?

Imperfections in structure

34(E) 'So here is the dislocation, and now imagine that we try to slide the top this way and the bottom this way – the atoms around the dislocation can rearrange themselves so in the next picture ...'.

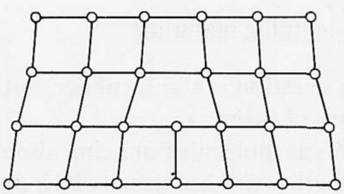


Figure A103

Draw the next picture. And the next. And the next. Write out the rest of the talk which might accompany the pictures.

35(E) A student writes the following short passage. Rewrite it to explain each of the points made, giving greater detail.

'Cracks occur in all substances. Cracks only propagate in materials with no long-range molecular order so materials with no long-range order undergo brittle fracture. Cracks are a macroscopic phenomenon.

'A few dislocations, foreign atoms, etc., can stop cracks from propagating by making a material ductile. Dislocations are a microscopic phenomenon. Many dislocations or foreign atoms can make a material harder. Harder materials are more likely to suffer brittle fracture.

'Temperature changes can also produce dramatic changes in properties. Most materials become more brittle at lower temperatures. For example, a rubber ball cooled in liquid nitrogen will shatter like a piece of china if dropped on the floor.'

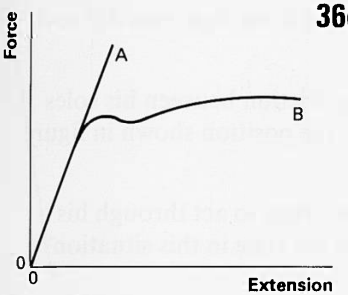


Figure A104

36(R) The force–extension curves of two steel wires of identical dimensions are shown in figure A104.

a Which wire is stronger?

b Which wire is tougher?

c Which one is made of high carbon steel and which one of mild steel?

d Briefly explain how the change in the concentration of carbon causes the difference in properties of the two wires.

Resolutions of forces and moments

37(P) A picture of weight W hangs from a hook by a single cord connected to two rings, as shown in figure A105, on the back of the frame. The picture does not touch the wall.

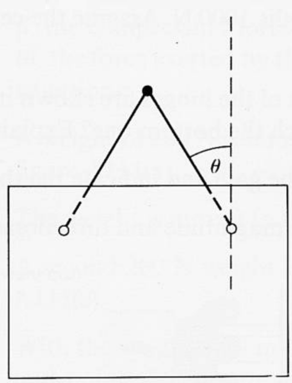


Figure A105

a Draw diagrams indicating all the forces acting on the picture and on the hook, showing their directions and points of application. The tension in the cord is T.

b How does the tension vary with the length of the cord? Should you use a short or long length to hang the picture?

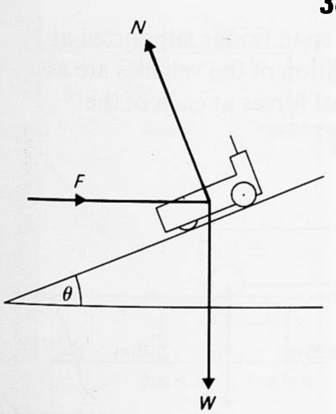


Figure A106

38(P) Figure A106 shows a dynamics trolley of weight W placed on a runway at an angle θ to the horizontal. It is held in place by a horizontal force, F. N is the force on the trolley normal to the runway.

a Resolve horizontally to find an expression for F in terms of N.

b Resolve vertically to find an expression for W in terms of N.

c Combine **a** and **b** to find an expression for F in terms of W.

d Resolve parallel to the runway to check your expression for F part **c**.

39(R) A climber rests for a moment as he climbs a fixed rope on a 45° rock face.

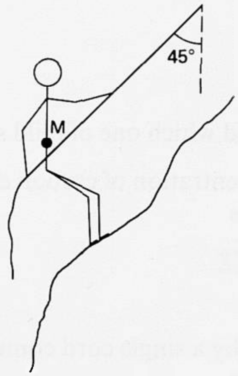


Figure A107

a If the rock is wet and there is virtually no friction between his soles and the rock, explain how he can stay in the position shown in figure A107.

b The climber weighs 707 N, which may be taken to act through his centre of mass, M. What is the tension in the rope in this situation? What is the force between the man and the rock?

c If there is enough friction between his boots and the rock so that he will not slip, which way should he lean to reduce the tension in the rope? The rope remains at the same angle to the vertical.
Is the force on the rock increased or reduced? Explain.

40(R) A five-bar gate is 2 m long and is supported by hinges 1 m apart. The gate weighs 1000 N. Assume the centre of gravity is 1 m from the pivot line.

a Sketches of the hinges are shown in figure A108. Which one is the top and which the bottom one? Explain.

b Sketch the gate and indicate the three forces acting on it.

c Find the magnitude and directions of the forces at the two hinges.

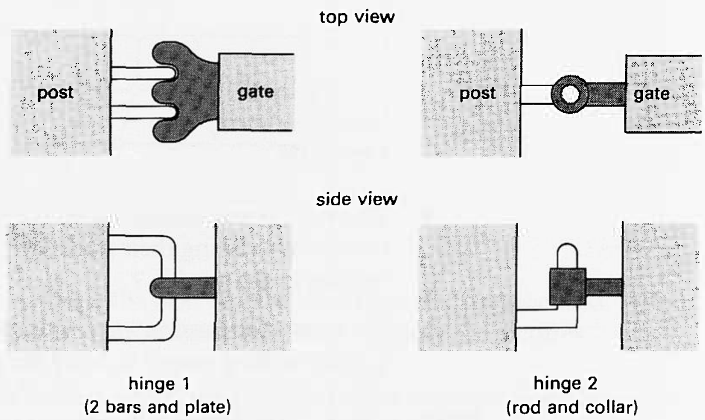


Figure A108

41(R) A tractor and trailer move across a single span bridge supported at points 21 m apart. The axle loads and position of the vehicles are as shown in figure A109. What are the vertical forces at each of the supports caused by this load on the bridge?

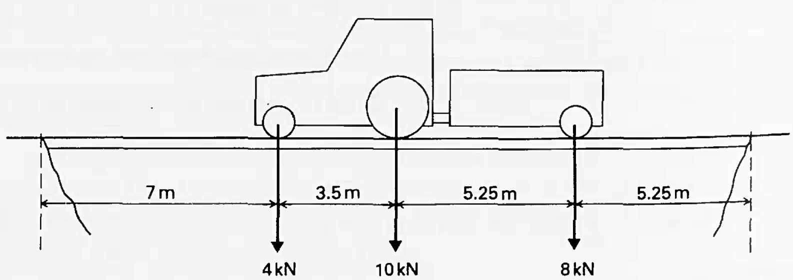


Figure A109

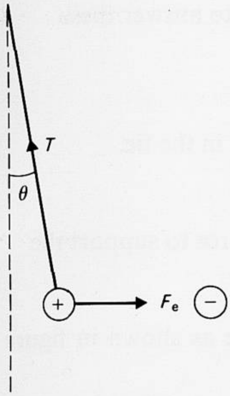


Figure A110

42(P) A light plastic ball (mass m) is suspended on a string.

a What is the tension in the string when the ball is hanging vertically?

The ball is now given an electric charge and figure A110 shows what happens when a second, oppositely charged ball, is brought near.

b Is the tension in the string now greater, less, or the same as before?

By resolving the forces on the ball vertically and horizontally respectively obtain expressions for:
i The tension in the string, T.
ii The electric force on the ball, F_e.

c For a small horizontal displacement of the ball, d, show that $F_e \propto d$.

A

43(R) A rigid beam of negligible mass is hinged to a wall, and held horizontal by a string as shown. Calculate:
i the tension, T, in the string
ii the compression force in the beam
iii the force exerted by the hinge on the beam in each of the following situations:

a A weight of 200 N is hung from the far end of the beam as shown in figure A111(a).

b The weight is moved to the mid-point of the beam – figure A111(b).

c A second 200 N weight is now added at the far end of the beam–figure A111(c).

d With the weights still in position, the string is shortened and tied to the mid-point of the beam, which remains horizontal. The string remains attached to the same point on the wall – figure A111(d).
Hints:
i The force at the hinge will not necessarily be exerted normal to the wall. You may find it easiest to resolve the force at the hinge into two components: one along the wall and another at right angles to the wall.
ii Remember to apply both the conditions for equilibrium.
iii Sketches are essential; you may even wish to confirm the results of your calculations by making scale drawings showing the force parallelograms or triangles.

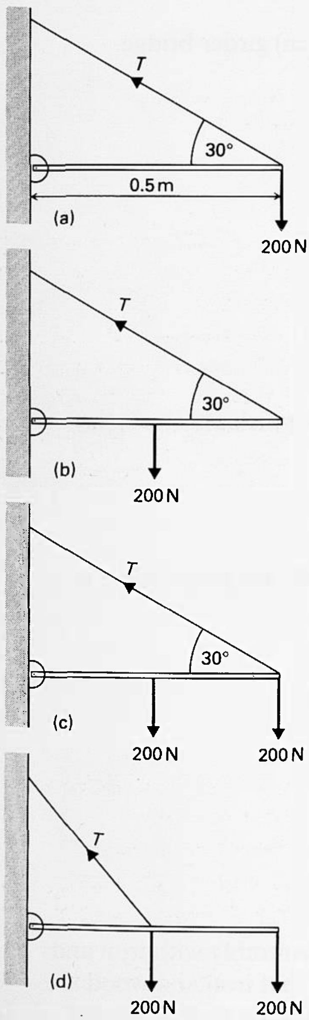


Figure A111

44(P) A wall-mounted crane lifts a mass of 1 tonne (1000 kg). The angle between strut and tie (figure A112) is 45°.

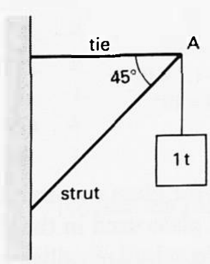


Figure A112

a Use the fact that the forces at A are in equilibrium to answer these questions.
i Is the strut in tension or compression?
ii Is the tie in tension or compression?
iii Calculate the values of the force in the strut and in the tie.

b Draw a triangle of forces for point A.

c Which of the two, strut or tie, provides a vertical force to support the load?

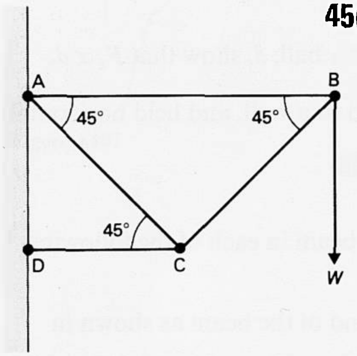


Figure A113

45(P) Four hinged rods are mounted in a vertical plane as shown in figure A113. A weight W is suspended from point B.

a By considering the forces acting at points B and C, find out which of the two rods are in compression (struts) and which are in tension (ties).

b Which two provide a vertical force to support the load?

c What is the function of the other two rods?

d (*Harder*) Figure A114 shows a simple (Warren) girder bridge.

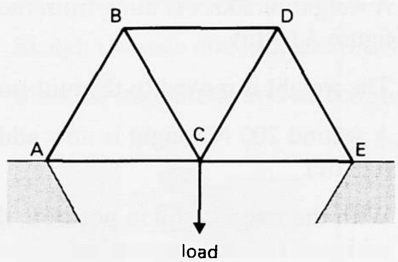


Figure A114

Which members are ties (in tension) and which are struts (in compression)?

Composite materials

46(F) The typical tensile strengths of some materials are given below in round numbers:

Material	Tensile strength/N m^{-2}
mild steel	10×10^8
wrought iron	5×10^8
wood, spruce:	
along grain	1×10^8
across grain	0.3×10^8
glass	0.3–1.7×10^8
concrete	0.04×10^8

Table A3

a The upper value for glass compares quite favourably with iron and wood. Why isn't glass used in the same way that iron and wood are used (for example, why are railway lines not made of glass instead of wrought iron; or boats made of glass instead of wood)?

b Why is plywood made the way it is (see figure A115)? Where would you expect to see plywood being used? Why? Why isn't plywood used for all purposes where wood is employed?

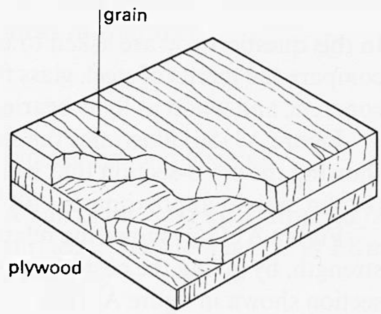


Figure A115

c Concrete has the lowest tensile strength of all the materials listed. How do you explain the widespread use of concrete in building?

47(R) Civil engineers have found that concrete pipes laid deep in the earth have sometimes cracked as shown (in cross-section) in figure A116(a).

a Explain, in terms of the various forces acting and the behaviour of concrete under stress, why the pipes crack as shown in figure A116(a).

b Why would you *not* expect to find a crack forming at the point X on the outside of the pipe?

The engineers found a solution. They cast round the pipes a tough plastic layer which shrank as it solidified, squeezing the pipe all round, as shown in figure A116(b).

c Why did this prevent the pipes from cracking?

d Suggest one other incidental advantage of encasing the pipes in plastic.

(Short answer paper, 1973)

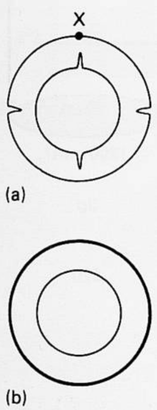


Figure A116

48(R) A vertical building is built from four very heavy identical concrete floor slabs, S, supported by light, slender steel pillars, P, as shown in figure A117. The architect needs to know the stress in the pillars on different floors.

Here are five possible values of the ratio of the stress in the pillars resting on the ground to the stress in the pillars supporting the uppermost slab:

A 4
B 2
C 1
D $\frac{1}{2}$
E $\frac{1}{4}$

Neglecting the weight of the pillars:

a What is the ratio if the rods at the bottom and top have the same diameter?

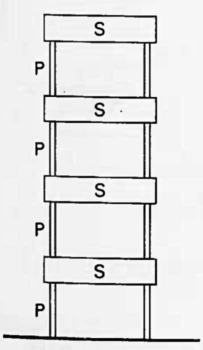


Figure A117

b What is the ratio if the pillars on the ground have twice the diameter of the pillars at the top?

(Coded answer paper, 1980)

49(R) In this question you are asked to use the information in the figure to compare the merits of steel, glass fibre (glass fibre-reinforced plastic), concrete, and wood as load-bearing materials in tension.

Figure A118(i) illustrates the strength of the materials in tension, by showing the cross-section that will just support a load of one tonne (10^3 kg, weight approximately 10^4 N).

Figure A118(ii) shows the relative cost of the materials per unit of strength, by giving the cost of one metre of material of the cross-section shown in figure A118(i).

Figure A118(iii) gives the cost of one cubic metre of each material, while figure A118(iv) illustrates their respective densities.

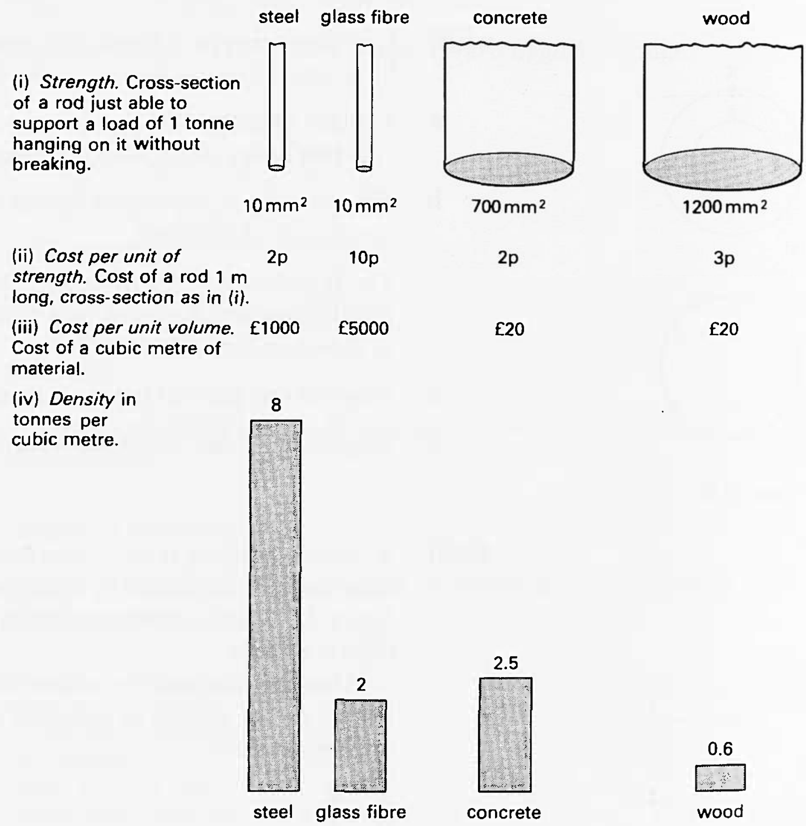


Figure A118
Strength, cost, and density of four materials.

a Say briefly what Figure A118(i) reveals about the variation in *tensile strength* from material to material.

b Comment, in the light of differences in the nature and structure of the materials, on the differences in their behaviour under stress.

c Discuss reasons for selecting or rejecting each material for each of **two** purposes. Choose your two purposes so as to *contrast* the properties of the materials, and to illustrate *different* aspects of the problem of choosing between the materials. Use the data given, and any further ideas of your own.

(Long answer paper, 1974)

Momentum and impulse

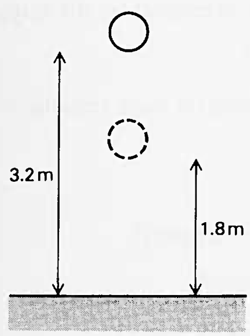


Figure A119

50(I) A ball of mass 0.1 kg is dropped from a height of 3.2 m onto a flat surface. It rises to a height of 1.8 m on the rebound (see figure A119). Calculate:

a the speed of the ball at the instant of impact,

b the speed of the ball immediately after leaving the surface,

c the change in energy of the ball caused by the impact,

d the change in momentum of the ball between the time of just touching the surface and leaving it (remember that momentum is a vector quantity),

e the average force exerted on the ball by the surface for an impact time of 0.04 s.

51(P) A long flat-topped railway truck of mass M which can move freely on a horizontal track, is at rest. A man of mass m is standing on the truck. The man suddenly runs at velocity v parallel to the direction of the track for time t and then stops.

a Describe the motion of the truck.

b What is the velocity of the truck whilst the man is running?

c What is its velocity after he stops?

d How far does the truck travel whilst the man is running?

52(R) A car of mass 600 kg travelling at a steady speed crashes into a rigid wall. From the time at which the car hits the wall until it stops, the engine compartment is crushed so the main body of the car continues to move forwards. The graph (figure A120) shows how the retarding force on the main body of the car varies with time from the initial impact ($t = 0$).

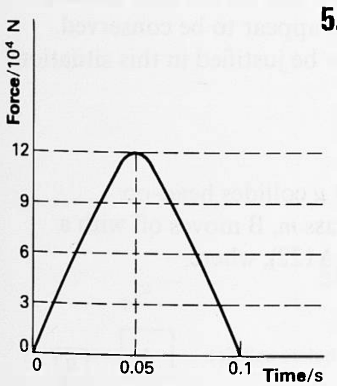


Figure A120

a What impulse is required to stop the car?

b By how much does the car's momentum change during the impact?

c Estimate the velocity of the car at the instant of impact.

d Sketch a graph of the velocity of the main body of the car against time until it came to rest. Explain how your graph is related to the one shown in figure A120.

53(P) Two air track vehicles with masses and velocities as shown in figure A121 move freely together and adhere on impact.

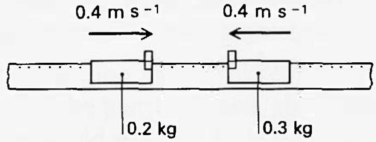


Figure A121

a What is the momentum of each vehicle before impact?

b What is the total momentum after impact?

c What is the *change in momentum* of each vehicle caused by the impact?

d What is the impulse on each vehicle at impact?

e The collision took 0.1 s. What is the average force on each vehicle during the collision?

f What is the final velocity of the two vehicles?

g What is the kinetic energy of each vehicle before impact?

h What is the final kinetic energy of the two vehicles?

i What has happened to the remainder of the kinetic energy?

54(E) In using Newton's Third Law of Motion difficulties often arise in deciding which forces are associated pairs.

a A freely falling object is acted on by a force W, the gravitational pull of the Earth. According to Newton's Law there should be another force, also equal to W, in the opposite direction. On what body does this act?

b A book rests on a table. There are two forces acting on this book. What are they? These forces are equal and opposite but are not the associated pair of Newton's Third Law. Explain this statement.

c A body falling towards the Earth is continually gaining momentum. Explain how the Law of Conservation of Momentum is not violated.

d A train starts from rest – momentum zero – and accelerates, gaining momentum, so again momentum does not appear to be conserved. How can the momentum conservation law be justified in this situation?

Elastic and inelastic collisions

55(L) When an object A of mass M and velocity u collides head-on elastically with a stationary object B of mass m, B moves off with a velocity v_B and A has a velocity v_A (figure A122), where

$$v_A = \frac{M-m}{M+m}\,u$$

$$v_B = \frac{2M}{M+m}\,u$$

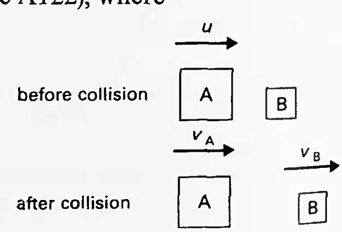


Figure A122

a Use these formulae to show that a golf ball will be driven from the tee at approximately twice the speed of the head of the golf club that hits it. Assume that the mass of the golf club is much greater than the mass of the ball.

b An alpha particle makes a head-on collision with a stationary helium nucleus. Show that the alpha particle will stop and the helium nucleus move off at the original speed of the alpha particle. (An alpha particle is a helium nucleus.)

c A fast-moving electron makes a head-on elastic collision with an atom. Show that it bounces back with almost its original speed. (The mass of the electron is tiny compared to the atomic mass.)

56(L)a Use the formula for v_B in question **55** to write down an expression for the kinetic energy of B in terms of m, M, and u.

b Divide your expression by $\frac{1}{2}Mu^2$ to show that kinetic energy of B is $\frac{4Mm}{(M+m)^2} \times$ initial kinetic energy of A.

c Show that very little kinetic energy is transferred between A and B if A and B are of very different mass, but that all the kinetic energy is transferred from A to B if A and B are of equal mass.

d An electron will lose a negligible amount of kinetic energy when it collides elastically with a gas atom, some 10 000 times more massive than itself. Estimate how accurately the electron energies would have to be measured to detect any kinetic energy loss.

57(R)a When considering collisions between alpha particles and atoms, or other scattering experiments, we ignore the effects of any electrons. An alpha particle makes a head-on elastic collision with a stationary electron. What is the ratio of its velocity after the collision to its velocity before? What is the percentage change in velocity? Is the approximation justified?

(The mass of the alpha particle is 7500 times greater than the mass of an electron.)

b A gas molecule moving at $400\,\mathrm{m\,s^{-1}}$ collides elastically head-on with the stationary piston of a gas syringe. What is its speed of recoil? You may assume that the recoil of the piston is negligible. The piston is now moved inwards at $1\,\mathrm{m\,s^{-1}}$. What is the new speed of recoil of the gas molecule? What will happen to the kinetic energy of all the gas molecules as the piston is moved inwards?

58(R) A 0.1 kg bullet travelling at $400\,\mathrm{m\,s^{-1}}$ and a 2000 kg car travelling at $0.02\,\mathrm{m\,s^{-1}}$ each collide with identical blocks of wood. The momentum of each before the collision is the same, but the effects produced are very different. Explain why this is so, even although in both collisions momentum is conserved.

(Special paper, 1974)

59(P) The simulated multiflash photograph in figure A123 shows a moving puck colliding with a stationary one of equal mass.

Take suitable measurements from the diagram to show either by scale drawing or by calculation that the total momentum in any direction is conserved.

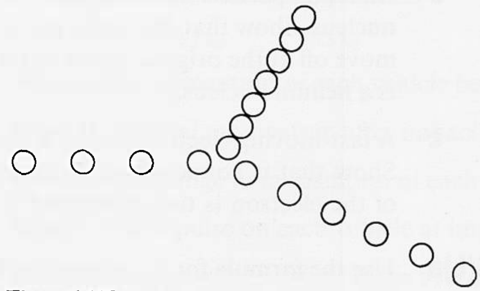


Figure A123

Kinetic theory of gases

60(P) The *molar volume* of a substance, V_m, is the volume occupied by one mole of its molecules. The molar volume of any gas is $2.24 \times 10^{-2}\,\mathrm{m^3\,mol^{-1}}$ at standard temperature and pressure (s.t.p.), which are 273 K and 1.01×10^5 Pa respectively.

a The density of air at s.t.p. is $1.29\,\mathrm{kg\,mol^{-1}}$. What is the molar mass of air?

b The ideal gas equation for 1 mole of gas is $pV_m = RT$. Calculate the value of R, the molar gas constant. What are the units of R?

c One mole of substance always contains the Avogadro number, L, of molecules, $6.02 \times 10^{23}\,\mathrm{mol^{-1}}$. How many molecules are there in 1 kg of air?

d On average, how far apart are air molecules at s.t.p.? How does this compare with the diameter of an atom 3×10^{-10} m?

e The Boltzmann constant, k, is the gas constant per molecule. What is its value?

61(P)a A cylinder of volume $1.0\,\mathrm{m^3}$ contains nitrogen gas at a pressure of 1 atmosphere (1.0×10^5 Pa) at room temperature (290 K). How many moles of gas does the cylinder hold? ($R = 8.3\,\mathrm{J\,mol^{-1}\,K^{-1}}$.)

b The molar mass of nitrogen is $0.028\,\mathrm{kg\,mol^{-1}}$. Gas is pumped into the cylinder until the pressure is increased to 6 atmospheres. What mass of gas does the cylinder now contain?

c The pressurized gas is released into the atmosphere. What volume of space will it now fill?

62(L) A molecule of mass m bounces backwards and forwards between the ends of a box of side l at a constant speed c_x, shown in figure A124.

Neglecting any recoil of the box and the finite time of each collision, find expressions for

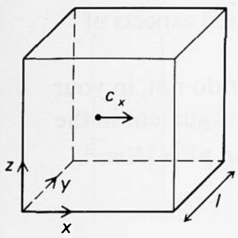


Figure A124

a the number of normal collisions the molecule makes on one end in one second;

b the change in momentum of the molecule at each collision;

c the total change in momentum at one end in one second;

d the mean force exerted by the molecule on the end.

In a real box there will be N molecules moving at random at various velocities c. Each velocity can be resolved into components parallel to three perpendicular edges of the box, such that $c^2 = c_x^2 + c_y^2 + c_z^2$. The average value of c^2 is $\overline{c^2}$ which equals $3\overline{c_x^2}$ as $\overline{c_x^2} = \overline{c_y^2} = \overline{c_z^2}$.

e What is the mean force exerted by all the molecules on one wall of the box in terms of $\overline{c_x^2}$?

f What is the mean pressure exerted on one wall of the box in terms of $\overline{c^2}$?

g The density of the gas is total mass/volume. Write down an expression for density in terms of l, N, and m. Rewrite your answer to **f** in terms of ρ and $\overline{c^2}$.

h The density of air at room temperature is about $1.2\,\mathrm{kg\,m^{-3}}$. Atmospheric pressure is 1.0×10^5 Pa. What is the mean square speed of molecules of air? What is their root mean square (r.m.s.) speed?

63(L) Consider six chosen molecules, each of mass 5×10^{-26} kg, of a gas contained in a box. Three are moving to the right with speeds 200, 300, and $500\,\mathrm{m\,s^{-1}}$, and three are moving to the left with speeds 100, 400, and $600\,\mathrm{m\,s^{-1}}$ (see figure A125.)

a What is their mean or average speed?

b What is their mean velocity?

c What is their mean kinetic energy?

d What is the speed of a molecule which has this mean kinetic energy?

e What is their root mean square speed?

f What is their mean momentum?

g If we had considered all of the molecules in the box, not just the chosen six, which of the quantities calculated in parts **a** to **f** above, would you expect to be zero?

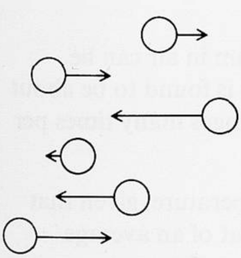


Figure A125

64(E) The following passage appears in a textbook:

'This indeed is how a physicist works; by trying to reason out the easiest problems first. In fact, he has to invent them. Think of it this way. The world is a very complicated place, and a physicist tries to see patterns of order and reason in all this complexity. His technique is never to try to deal with all aspects of a physical situation as it really is. Instead, he deals with simplified models of selected aspects of reality.'

Discuss whether the ideas in this passage do, or do not, in your opinion, give a good description of the theoretical argument in the kinetic theory of gases used to derive the expression $pV=\frac{1}{3}Nm\overline{c^2}$.

You should include in your discussion

a the extent to which the ideas in the passage apply to the derivation of $pV=\frac{1}{3}Nm\overline{c^2}$, giving reasons for your view;

b an account of aspects of the situation which are being simplified or selected;

c a description of the ways in which the argument might give wrong answers in a real concrete situation because of the simplifying assumptions it makes.

(Long answer paper, 1976)

65(P) Use the following data to answer the questions below: the Boltzmann constant, k, is $1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$; the r.m.s. speed of nitrogen molecules at 273 K is $490\,\mathrm{m\,s^{-1}}$.

a What is the mean translational kinetic energy of a nitrogen molecule at 273 K?

b What is the mass of a nitrogen molecule?

c What is the mean kinetic energy of an oxygen molecule at 273 K? Of a helium molecule at 273 K?

d A nitrogen molecule is 7 times more massive than a helium atom. What is the r.m.s. speed of helium atoms at 273 K?

66(P) The speed of smoke particles in thermal equilibrium in air can be measured from Brownian motion observations. It is found to be about $10\,\mathrm{mm\,s^{-1}}$. Of course, the direction of motion changes many times per second.

a Estimate the speeds of air molecules at room temperature, given that the mass of an air molecule is 5×10^{-26} kg and that of an average smoke particle is 1×10^{-16} kg.

b Compare this result with the value obtained from kinetic theory using the following data (again given only to one significant figure): atmospheric pressure is 1×10^5 Pa; molar mass of air is $3 \times 10^{-2}\,\mathrm{kg\,mol^{-1}}$; molar volume at s.t.p. is $2 \times 10^{-2}\,\mathrm{m^3\,mol^{-1}}$.

67(L) When bromine liquid is released into a tube which has been evacuated, the bromine vapour fills the tube almost instantaneously.

a Find the r.m.s. speed of bromine molecules at room temperature. The molar mass of bromine gas is $0.16\,\mathrm{kg\,mol^{-1}}$.

b How long will it take to fill an evacuated tube 0.5 m long?

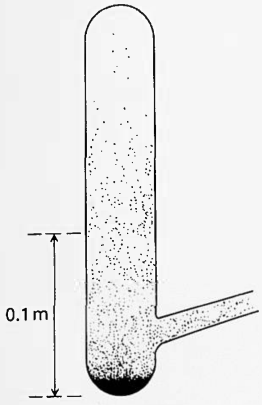


Figure A126

When bromine liquid is released into the tube containing air at atmospheric pressure, it takes about 500 seconds for an average bromine molecule to have travelled 0.1 m from the bottom of the tube. The top of the tube is still colourless, the bottom dark brown. And this point, 0.1 m up, is about 'half brown' in colour. (See figure A126.)

c The direct distance the bromine molecule travels through the air is calculated theoretically to be $\sqrt{N}$ times the mean free path, where N is the number of collisions the molecule makes along its path. What total distance did the molecule actually travel in 500 s? Hence find the number of collisions, N, the molecule made in 500 s.

d What is the mean free path, λ, of the bromine molecule, that is, the average distance between collisions?

e Theory shows that the mean free path $\lambda \approx \dfrac{1}{\pi n d^2}$, where n is the number of molecules per unit volume of the gas and d is the molecular diameter. The Avogadro constant is $6.0 \times 10^{23}\ \mathrm{mol^{-1}}$ and the molar volume is $0.022\ \mathrm{m^{-3}\ mol^{-1}}$. Use this information to estimate the radius of a bromine atom.

f Has it been assumed that bromine and air molecules are about the same size? Explain.

68(P) The bromine diffusion through air experiment enabled us to find the mean free path of bromine in still air in question **67**.

a Suppose some liquid bromine was dropped in the corner of a large room, say, 6 metres wide. How long would it take for an average bromine molecule to diffuse across the room?

b Your answer to part **a** is very large. If somebody dropped a stink bomb in the corner the smell would take only a minute or two to cross the room. Explain.

69(L) Gas at pressure p occupies a volume V in the cylinder shown in figure A127. The area of the piston is A.

a What is the force on the piston?

b The gas expands, pushing the piston back by a distance Δl. What is the work done by the gas?

c Write your answer to **b** in terms of the change in volume, ΔV.

d Suppose the gas is compressed and the volume decreases by ΔV. How much work is done on the gas?

e Mention two assumptions that you had to make to answer these questions.

f When you pump up the tyres of a bicycle the air in the pump gets hot. When you let the air out suddenly by removing the valve it cools. Relate these observations to the work done on or by the gas.

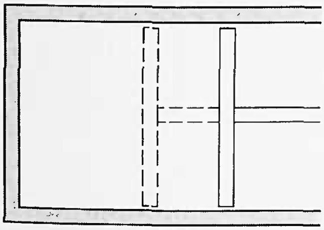


Figure A127

Unit B
CURRENTS, CIRCUITS, AND CHARGE

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B

SUMMARY OF THE UNIT

SUMMARY OF THE UNIT

INTRODUCTION

This Unit is about the nature of electric charge, how it can move in conductors and in empty space to form currents, and how it can be stored at rest, for example on capacitor plates.

These ideas are central to the rest of the course, not least because approximately half the mass of the Universe (including you!) is composed of electrically charged particles. More specifically, the circuit ideas will be used again in electronics, in Units C, 'Digital electronic systems' and I, 'Linear electronics, feedback and control'; charge and the concept of potential difference will be used in Unit E, 'Field and potential', Unit F, 'Radioactivity and the nuclear atom', and Unit J, 'Electromagnetic waves'.

Section B1 THINGS WHICH CONDUCT

Flow

The effects of an electric current are quite familiar, but the processes actually going on in the conductor are far from obvious. There is usually nothing to see, and even when there is it doesn't help us much to understand more about what is happening (for instance, the glowing of a light bulb filament or the light emitted by an L.E.D.). We are forced to make inferences from circumstantial evidence, to build up a picture from a number of clues rather than look to the result of one single conclusive experiment. (You might, for example, ask yourself how you know that molecules exist and that they move – are you convinced by the evidence, granted that you will never see one?)

Electric current is charge on the move – the charge may be of either sign and can be a 'fundamental' particle like an electron (which we shall be looking at again at the end of the Unit) or a charged atom or group of atoms called an *ion*. Some further experiments which lead to this view, based on capacitors, are considered in Section B3. Here we concentrate on the aspect of flow.

Experiments with simple series circuits show that the *order* of the components does not matter: a rheostat to control the brightness of a lamp can be placed on either side of the lamp; an ammeter reads the same wherever it is put, showing that current is not 'used up' in the circuit.

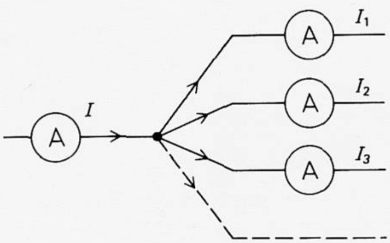


Figure B1
Multi-branching in a circuit.

Similarly, in a parallel circuit where there is a branch (figure B1) the reading of the meter in the main part, I, is the sum of the readings in the branch circuits.

Kirchhoff's First Law

$$I = I_1 + I_2 + I_3 + \ldots$$

This is usually referred to as Kirchhoff's First Law.

In its full form the Law states:
At a junction in a circuit,
Σ(current arriving) $=$ Σ(current leaving)
which you will often find written more formally in textbooks as
Σ(current arriving) $= 0$, taking account of the sign (direction) of current.

These statements about series and parallel circuits are, of course, very useful in helping us to do calculations and to make quantitative predictions about circuit behaviour. They are also important, though, in helping to establish the idea of a current as a flow of something indestructible which just keeps circulating round. It would be difficult to think of any other hypothesis which would explain Kirchhoff's First Law.

DEMONSTRATION B1
Conduction by coloured salts

The movement of charge in one particular case can be demonstrated – the migration of coloured ions in a liquid as current flows. This brings out two major points:

i The direction of motion. For a given current direction (which is conventionally taken from the positive battery terminal to the negative round the circuit) the charge flow can be either way depending upon its sign (figure B2). We believe that in a *metal* the charge carriers are negative (electrons) and therefore move in the opposite direction to the conventional current.

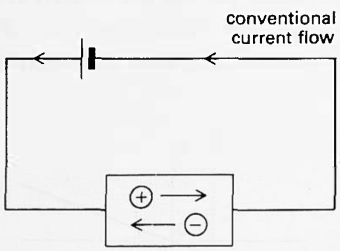


Figure B2
Movement of ions.

ii The speed of the ions. One might intuitively think that the charges move extremely quickly as they carry the current. Although electrical effects seem to happen instantaneously – a lamp comes on as soon as a switch which may be quite far away is closed – observation shows that the charges actually move quite slowly. An important equation which relates these facts is:

QUESTION 1

$I = AvnQ$

(A is the cross-sectional area of the conductor, n the density of charge carriers, v their speed, and Q the charge carried by each one.)

This equation can be used to estimate the speed of charge carriers in a liquid. Of course, if there is no resistance to motion (for example an electron beam in a vacuum) the charges *can* accelerate to very high velocities. This equation can still be used, so that for a given current large values of v imply small values of n, the charge carrier density.

Energy transformation

When a current flows through any conductor energy is transformed. The amount of energy transformed between two points per unit charge passed is called the *potential difference* (p.d.) between the points.

$$V = \frac{W}{Q}$$

DEMONSTRATION B2
Measuring p.d. without a voltmeter

(V is the p.d., W the energy, and Q the charge; in units, 1 volt $=$ 1 joule per coulomb.)

This can also be expressed as

QUESTIONS 3 to 6

$$W = VQ$$

Dividing both sides by the time t,

$$\frac{W}{t} = \frac{VQ}{t}$$

or

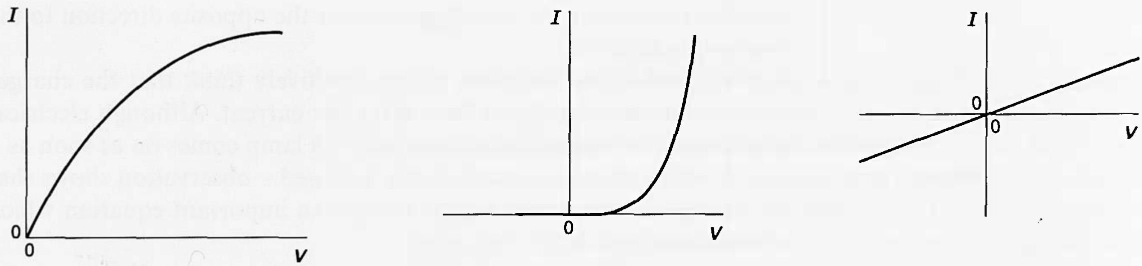
$$P = VI$$

(P is the power, I is the current; in units, 1 watt = 1 volt × 1 ampere)

Resistance

EXPERIMENT B3
Two-terminal boxes

The current through a component depends on the p.d. across it. The graph of such a relationship is called the 'characteristic' of the component, and it is a useful way of summarizing how the component behaves (figure B3).



(a) Lamp (b) Diode (c) Metal wire

Figure B3
Current–p.d. graphs for some conductors.

For any component the ratio V/I is called the *resistance*. In general it will not be constant (see lamp and diode graphs), but for some conductors, particularly metals, I is proportional to V (linear graph through origin). This is a statement of Ohm's Law. (The temperature should be constant for the Law to apply.)

For ohmic conductors:

$$R = \frac{V}{I} = \text{constant}$$

QUESTIONS 7 to 11

Using this definition of resistance we can now write the power converted in a resistor (VI) in two alternative and equivalent forms:

$$P = I^2R$$

and

$$P = V^2/R$$

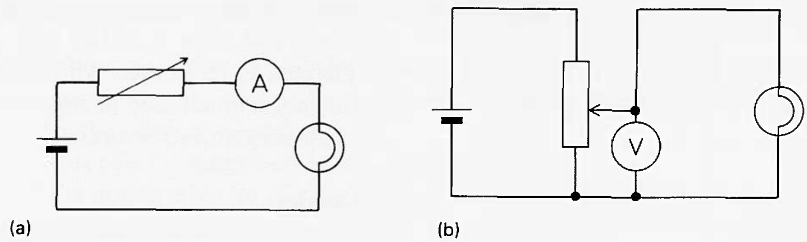


Figure B4
(a) Rheostat controlling current.
(b) Potentiometer controlling applied p.d.

EXPERIMENT B4
Comparison of rheostat and potentiometer

Control of current and p.d.

A rheostat (variable resistor) can be used to control the current in a circuit *between maximum and minimum limits* set by the resistance of the rheostat.

A potentiometer (potential divider) can be used to 'tap off' a certain proportion of a battery's voltage. The full range, from zero to maximum p.d., is possible.

Note that a potentiometer does not have to deliver current, but there has to be current flowing through the rheostat.

QUESTION 10

Combination of resistors

It is useful to consider two simple but very useful combinations of resistors, *series* and *parallel* (figure B5). If R is the value of the single resistance which can replace the combination:

series $R = R_1 + R_2$

parallel $\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2}$

The formulae generalize to any number of resistors.

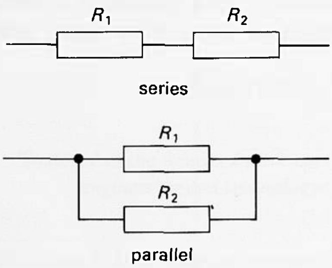


Figure B5
Resistor combinations.

What does resistance depend on?

Three factors determine the resistance of a conductor: what it is made of, its dimensions, and (usually) its temperature. So for a given material at a fixed temperature only the shape is important.

DEMONSTRATION B5
Effect of size and material on resistance

Simple experiments or a theoretical argument (based on the series and parallel resistance formulae) show that for a conductor of length l and cross-sectional area A (figure B6)

QUESTION 15

$$R \propto \frac{l}{A}$$

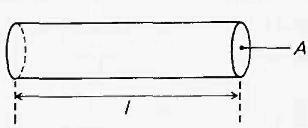


Figure B6

HOME EXPERIMENT BH1
The resistor

Notice that since R is inversely proportional to A, fat wires will conduct better than thin ones (other things being equal). Conductors which have to carry high currents (for example, to the starter motor of a car) are thick; those which carry only small currents – say on a printed circuit board in a radio – can be much thinner.

B

QUESTION 16

The resistance of a wire will change when it is stretched. Its length increases and cross-sectional area decreases: both these changes cause an increase in resistance. An important application of this effect is the *strain gauge*, much used in engineering to monitor and measure stresses in machinery and structures.

Resistivity

We can introduce a constant of proportionality into the relationship $R \propto l/A$:

QUESTION 17

$$R = \rho \frac{l}{A}$$

What are the units of ρ?

where ρ is a constant for a given material at a given temperature. It is called the *resistivity*.

QUESTIONS 13, 14

The range of values of ρ varies enormously by a factor of about 10^{26}. For a good conductor, copper, ρ is about $10^{-8}\,\Omega\,\text{m}$; for an insulator such as PTFE it is about $10^{18}\,\Omega\,\text{m}$. An important class of materials lies in the middle of the range – the *semiconductors.*

DEMONSTRATION B6
Effect of temperature on resistance

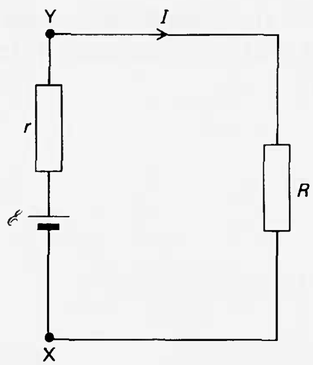
The resistivity also varies with temperature according to this classification. For plastic materials and other good insulators ρ decreases as they become hotter; metals behave in the opposite way and they become poorer conductors. The resistivity of semiconductors decreases markedly with rising temperature, and this effect is used, for example in the thermistor, for detecting or measuring small temperature changes.

Section B2 CURRENTS IN CIRCUITS

Electromotive force (e.m.f.)

EXPERIMENT B7
Four-terminal boxes

Electromotive force is a property of a power supply and is measured in volts (joules/coulomb). (Note that it is *not* a force!) However, unlike the p.d. across, say, a heating coil, e.m.f. describes the energy transformation *into* electrical energy. An e.m.f. $\mathscr{E}$ delivering current I is supplying power *to* the circuit at a rate $\mathscr{E}I$.



X and Y are the real cell terminals

Figure B7
Internal and external resistance.

A real power supply will have a resistance of its own (its *internal resistance*), and can be represented by an equivalent circuit having the internal resistance r in series with an e.m.f. $\mathscr{E}$ (figure B7). The power delivered by the supply is $\mathscr{E}I$, and the power transformed in the circuit is I^2r (in the supply itself) and I^2R (in the load resistance, R). By the Law of Conservation of Energy,

$$\mathscr{E}I = I^2R + I^2r \qquad \text{or}$$

$$\mathscr{E} = I(R + r)$$

Re-arranging,

$$IR = \mathscr{E} - Ir$$

$$V_{\text{load}} = \mathscr{E} - Ir$$

QUESTIONS 21, 22

where V_{load} is the p.d. across the external resistance R.

Effect of a load on the p.d. of the supply

The above equation shows that when a load draws current the actual p.d. across it is *less* than the e.m.f. by an amount Ir (the potential drop across the internal resistance).

DEMONSTRATION B8
Drop in terminal p.d. of source on load

This effect is important in two situations:

i If r is appreciable (or if a high current is drawn), then the actual p.d. across the circuit will be appreciably less than the e.m.f. of the source. Always use a voltmeter to check the actual p.d.!

HOME EXPERIMENT BH2
The voltaic pile

EXPERIMENT B9
Comparison of voltmeters

ii A voltmeter will only give an approximate indication of e.m.f. If the voltmeter's resistance is not *much* higher than the internal resistance, it will draw an appreciable current, and so the reading will be less than the e.m.f. of the source. (The voltmeter reading will be correct – but it will not be equal to the e.m.f.) The equation $V_{\mathrm{load}} = \mathscr{E} - Ir$ shows that only if $I = 0$ ('infinitely high' meter resistance) will the measured value equal the e.m.f.

The maximum current which can be drawn from a source is $\mathscr{E}/r$ (when $R = 0$), but this size of current (the *short-circuit* current) would rapidly damage many types of source.

DEMONSTRATION B10
High resistance voltmeter

It is important to choose the appropriate measuring instrument (voltmeter, oscilloscope, electrometer, etc.) for a particular job.

Digital meters have higher resistances than moving coil meters.

Power delivered to a load

QUESTION 22

'Systems' in the Reader *Physics in engineering and technology*

If the load resistance is either very high or very low the power transferred to it from the supply will be very small. The power is a maximum when $R = r$, and under this condition the source is working at it most efficient (as far as delivering useful power is concerned).

The potentiometer

EXPERIMENT B11
Potentiometer balancing an e.m.f.

QUESTIONS 20, 23 to 25

If a battery supplies a p.d. V across a uniform wire, then the p.d. across every centimetre length of the wire is the same. There is a uniform potential gradient along the wire. The potential drops in the direction of the current (from positive to negative): the potential gradient is therefore positive (rising) in the *opposite* direction to the current flow. Note that it is very often convenient to take point X, say, as being at zero potential (though any other point could be used). We can then give a value to the potential at any other point such as Y. In figure B8, Y is at a higher potential than point X.

If a cell is added in series with the voltmeter (figure B9), then by adjusting the length l a position can be found at which the voltmeter reading is zero. In this state of balance there is no p.d. across the meter; the potentials on either side of it are equal. No current flows through the meter or the cell, and the length l is a measure of the cell's e.m.f. Because it does not draw any current, the potentiometer is an excellent method for accurate measurements of e.m.f.

QUESTION 24

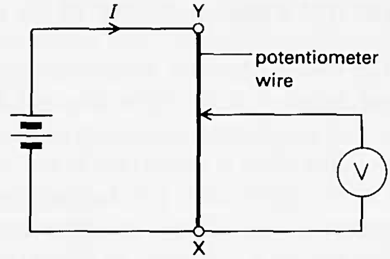


Figure B8
A rising potential gradient from X to Y.

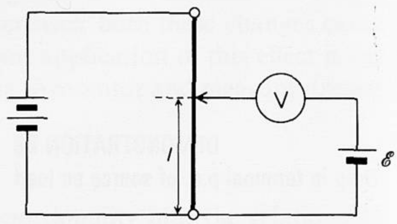


Figure B9
A balanced potentiometer.

Bridge circuits

EXPERIMENT B12
Using two potentiometers to make a bridge circuit

If the cell in figure B9 is replaced by a second potentiometer, then the arrangement can still be balanced (no current through the voltmeter), as in figure B10. The two negative terminals are joined to provide a common zero potential point for both sides. Two power supplies are not necessary, since both potentiometers can be driven from the one (see figure B11). This arrangement is called the Wheatstone bridge.

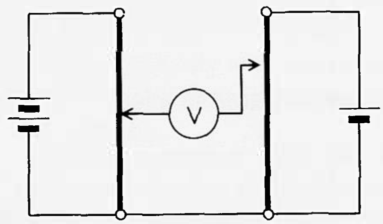


Figure B10
Two potentiometers in balance.

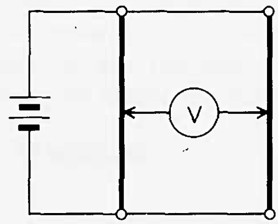


Figure B11
Wheatstone bridge.

EXPERIMENT B13
Detection of small resistance changes

READING
Applications of Wheatstone bridge circuits (page 108)

If one of the two sliding contacts is adjusted slightly, then some current will flow through the meter. If the voltmeter is replaced by a sensitive galvanometer, then small out-of-balance movements can easily be detected.

Since the wire is uniform, equal movements of the contact correspond to equal changes in resistance. For small changes in resistance, the out-of-balance current is proportional to the change in resistance. This gives an extremely sensitive method of detecting small resistance changes in quite large resistances, and is the usual circuit to use with, for example, resistance thermometers or strain gauges.

Kirchhoff's Second Law

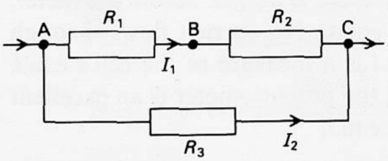


Figure B12
A circuit loop.

If we imagine a clockwise journey round the loop circuit of figure B12, starting and finishing at A, then the total change in potential must be zero. From A through B to C, there is a potential drop of $(I_1R_1+I_1R_2)$. From C back to A through R_3 there will be a rise (against the current) of I_2R_3. Hence $I_1R_1+I_1R_2-I_2R_3=0$. This can be put in a very concise form, to say that if we sum round any complete loop in a circuit in which there is *no* source of e.m.f.,

$$\Sigma IR = 0$$

remembering that individual 'IR' terms will be negative if the sense is against the current flow in that branch.

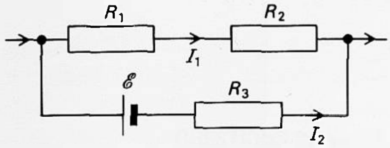


Figure B13
A loop containing a source of e.m.f.

If the loop includes a source of e.m.f. $\mathscr{E}$, of negligible internal resistance, as in figure B13, then a similar argument shows

$$I_1R_1 + I_1R_2 - I_2R_3 = \mathscr{E}$$

QUESTION 27

or again, round any complete loop

$$\Sigma IR = \Sigma\mathscr{E}$$

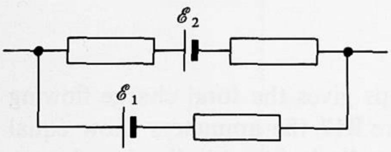


Figure B14
Cells in opposition.

where the righthand side is the total net e.m.f. in the loop. The sign of $\mathscr{E}$ is taken as positive if the imaginary journey passes *from* the positive cell terminal around the rest of the circuit (*i.e.*, from negative *to* positive inside the cell). In figure B14 $\mathscr{E}_1$ is positive and $\mathscr{E}_2$ negative, for a clockwise circulation.

B

Section B3 ELECTRIC CHARGE

QUESTION 28

Electric charge, like mass, energy, and momentum, is a quantity which is conserved. When an object is charged, nothing is created, the available charge is simply re-distributed.

An electric current is a movement of charge, and the current I is the flow of charge per second. For steady currents the charge flowing around a circuit can be calculated using the equation

Charge flowing (in coulombs)
= Rate of flow of charge (in amperes) × time (in seconds)

$$Q = I \times t$$

EXPERIMENT B14
Capacitors and charge

QUESTIONS 29, 30

In experiments on charging and discharging capacitors, surges of current carry charges around the circuit. These currents rapidly fall to zero showing that the capacitor will only let a certain quantity of charge flow. Using an oscilloscope shows that the current carrying the charge around the circuit changes in the way shown in figure B15. The charge flowing can be calculated from the area under the current–time graph. This can be shown by dividing the area under the graph into vertical strips. Each strip has the same narrow width, representing a short time interval, Δt. During this short period of time the height of the strip representing the current I changes very little. The area of the rectangular strip represents the small charge ΔQ flowing in time Δt (figure B16).

$$\Delta Q = I\Delta t$$

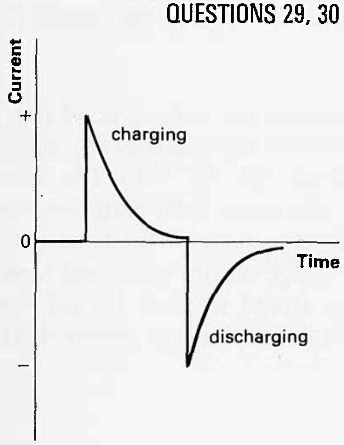


Figure B15

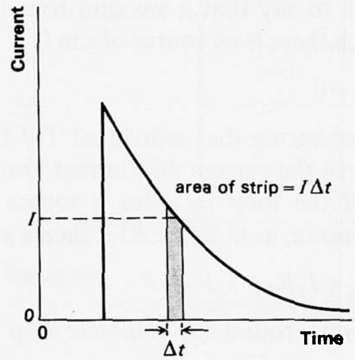


Figure B16

Summing the area of all the strips gives the total charge flowing during charge or discharge. In figure B17 the ammeters show equal pulses of current during charging or discharging, indicating that as much charge flows into one plate as off the other. The capacitor stores no net charge (figure B18).

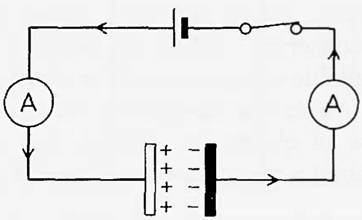


Figure B17

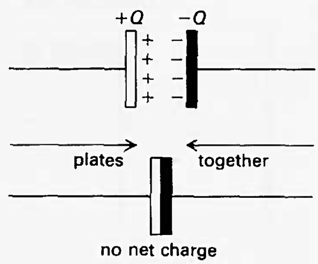


Figure B18
Net charge is zero.

QUESTIONS 31 to 33

DEMONSTRATIONS B15 and B16
Charging a capacitor at a constant rate
Spooning charge

Charging a capacitor using a constant current, or 'spooning' charge from a high voltage electrode, shows that the potential difference, V, across the capacitor plates is proportional to the quantity of charge, Q, which has moved around the circuit (figure B19). The constant of proportionality is called the capacitance, and is given the symbol C.

$Q = CV$

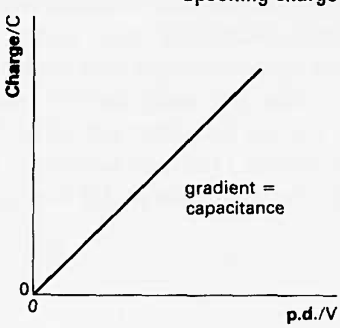


Figure B19
$Q \propto V$.

The unit of capacitance is the coulomb per volt, or farad (F). The farad is a very large unit, and most practical capacitances are measured in microfarads (μF, 10^{-6} F) or picofarads (pF, 10^{-12} F). The value of capacitance indicates the amount of charge on each plate per volt of potential difference across the plates. Both plates store the same quantity of charge, but since there is positive charge on one plate and negative charge on the other, the net charge stored is zero. To say that a capacitor stores a charge of Q means that one plate has gained charge Q and the other has lost Q.

Capacitors in parallel and series

When capacitors are connected in parallel, the potential difference across both capacitors is the same, and the charges on the plates can be added. So twice the charge moves around the circuit in figure B20(b) as in figure B20(a), and the capacitance of the circuit is doubled.

QUESTIONS 34 and 35 Capacitances in parallel add:

$$C = C_1 + C_2$$

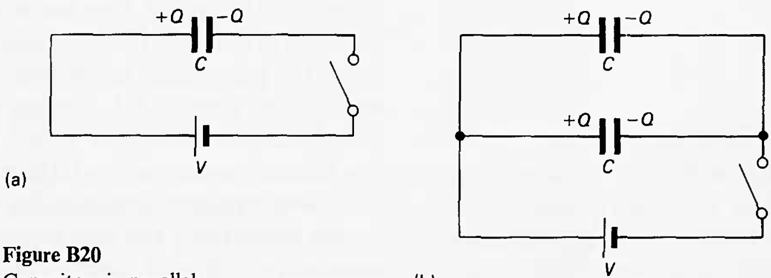


Figure B20
Capacitors in parallel.

When capacitors are connected in series across a supply voltage, the same current must charge both capacitors (Kirchhoff's First Law), and so the charge on each plate is the same – figure B21(a). Applying Kirchhoff's Second Law shows that the potential differences across the capacitors must add up to the supply voltage – figure B21(b).

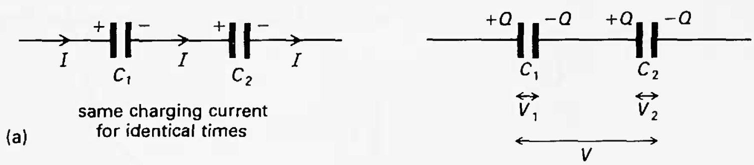


Figure B21
Capacitors in series.

$$V = V_1 + V_2$$

Dividing by Q (which is the same for both capacitors) gives

$$\frac{V}{Q} = \frac{V_1}{Q} + \frac{V_2}{Q}$$

and so

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

QUESTION 36 where C is the total effective capacitance of the capacitors in series.

Energy stored in a capacitor

QUESTION 37

DEMONSTRATION B17
Energy stored in a charged capacitor

DEMONSTRATIONS B18 and B19
Energy $\propto V^2$

When a capacitor discharges, charge moves through a potential difference as it flows off one plate and onto the other. If charge Q (in coulombs) moves through a potential difference of V (in volts), the energy transformed is QV(in joules). As the discharge continues V falls, and so the last charges to move around the circuit move through a smaller p.d. than the first. This can be compared with releasing a stretched spring, where the restoring force decreases as the spring contracts. The spring does less work in the last centimetre of contraction than in the first. The total energy stored by the capacitor is the area under the p.d.–charge graph (figure B22). The rectangular strip represents a tiny charge, ΔQ, flowing off the capacitor. During this small change the p.d. across the plates, V, remains approximately constant. The energy transformed is $V\Delta Q$, which is the area of the strip. Dividing the whole area into similar strips we find the total energy transformed during discharge is the area under the graph $=\frac{1}{2}Q_0V_0$. Combining this equation with $Q=CV$ gives three expressions for the energy stored in a capacitor.

$$\text{Energy stored} = \tfrac{1}{2}Q_0V_0 = \tfrac{1}{2}CV_0{}^2 = \tfrac{1}{2}\frac{Q_0{}^2}{C}$$

where Q_0 and V_0 are the initial charge and p.d.

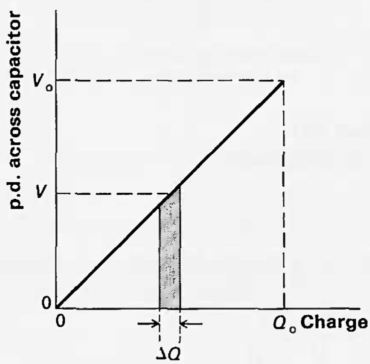


Figure B22
Energy as area of strip.

QUESTION 38 to 40

Capacitors are not viable as large-scale energy storage devices because of the large voltages required to store worthwhile amounts of energy. Furthermore, when supplying a current the voltage cannot be held at a steady value as can that of a battery or generator. The ideas linking charge, potential difference, and energy used here will be important in Unit E, 'Field and potential', when electric fields are studied.

Analogy between spring and capacitor

Spring	Capacitor
$F \propto x$	$V \propto Q$
$F = kx$	$V = \dfrac{Q}{C}$
Energy $= \frac{1}{2}Fx$	Energy $= \frac{1}{2}VQ$
$= \frac{1}{2}kx^2$	$= \frac{1}{2}\left(\dfrac{1}{C}\right)Q^2$

Exponential decay of charge

When a capacitor is discharged through a resistor the current falls, producing the decay curve shown in figure B23. This curve has a constant ratio property: if the current is recorded at equal intervals of time, then $I_1/I_2 = I_2/I_3$. This sort of change is called exponential decay, and it crops up in a very wide variety of situations in virtually every branch of science.

B

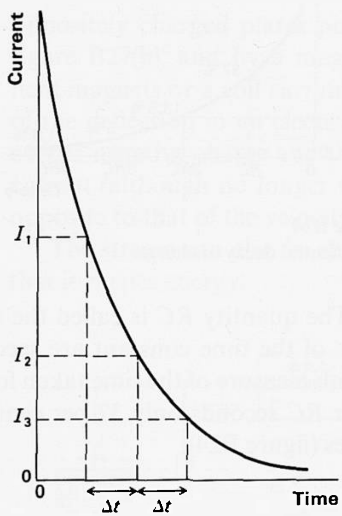


Figure B23
Exponential decay.

DEMONSTRATION B20
Decay of charge

Why does the curve have this shape? The p.d. across the capacitor which drives the current through the resistor depends on the charge left on the capacitor plates. As the current flows, charge is removed from the plates causing the p.d. to drop, which in turn reduces the current. The current falls because of the current itself.

QUESTIONS 41, 42

p.d. across capacitor $V = Q/C$

but $I = V/R$

so discharge current $I = \dfrac{Q}{RC}$

Energy stored in a capacitor

QUESTION 37

DEMONSTRATION B17
Energy stored in a charged capacitor

DEMONSTRATIONS B18 and B19
Energy $\propto V^2$

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$$\text{Energy stored} = \tfrac{1}{2}Q_0V_0$$
$$= \tfrac{1}{2}CV_0^{\,2}$$
$$= \tfrac{1}{2}\frac{Q_0^{\,2}}{C}$$

where Q_0 and V_0 are the initial charge and p.d.

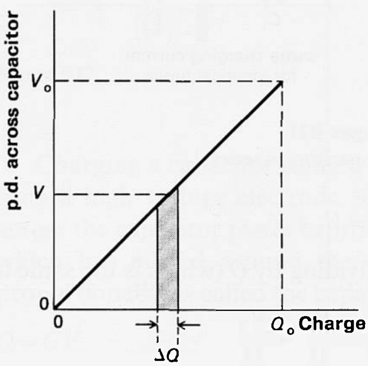

Figure B22
Energy as area of strip.

QUESTION 38 to 40

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Energy $= \frac{1}{2}Fx$	Energy $= \frac{1}{2}VQ$
$= \frac{1}{2}kx^2$	$= \frac{1}{2}\left(\dfrac{1}{C}\right)Q^2$

Exponential decay of charge

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B

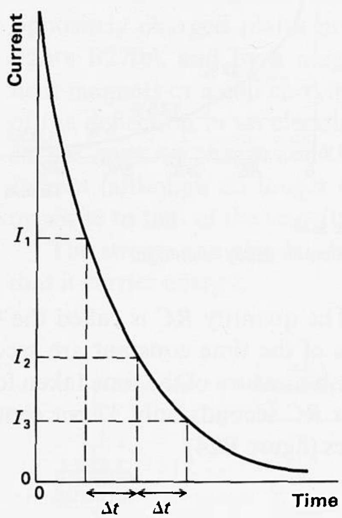


Figure B23
Exponential decay.

DEMONSTRATION B20
Decay of charge

Why does the curve have this shape? The p.d. across the capacitor which drives the current through the resistor depends on the charge left on the capacitor plates. As the current flows, charge is removed from the plates causing the p.d. to drop, which in turn reduces the current. The current falls because of the current itself.

QUESTIONS 41, 42

p.d. across capacitor $V = Q/C$

but $I = V/R$

so discharge current $I = \dfrac{Q}{RC}$

Because RC is constant for a particular circuit, $I \propto Q$, and the graph of charge against time has the same shape as the graph of current against time (figure B23).

The current, I, is the rate of flow of charge

$$I = -\Delta Q/\Delta t$$

and so

$$\Delta Q/\Delta t = -Q/RC$$

the negative sign indicating that the flow of charge decreases Q.

The rate of flow of charge at any instant is proportional to the quantity of charge left on the capacitor. For any exponential growth or decay the rate of change of a particular quantity is proportional to the amount of that quantity. Exponential changes are important in many fields including population growth, use of resources, and radioactive decay. In the last case, for example, the number of nuclei decaying per second is proportional to the number of those nuclei remaining in the sample.

Unit F, 'Radioactivity and the nuclear atom'

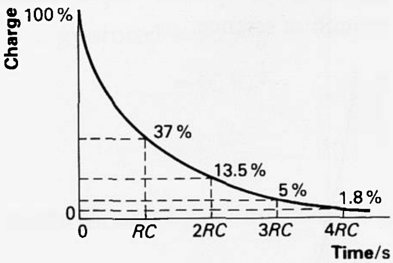


Figure B24
Exponential decay of charge.

QUESTION 44

The quantity RC is called the time constant of the circuit, and the units of the time constant are seconds. The time constant is a rule of thumb measure of the time taken for a capacitor to charge or discharge. After RC seconds only 37 per cent of the original charge is left on the plates (figure B24).

Logarithmic graphs

All exponential changes have the constant ratio property described above. The series:

$10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \ldots$

also has this property (it increases by a factor of ten each time). However, the logarithms of the numbers in that series:

1 2 3 4 5 6 7 ...

increase in equal amounts (a linear change).

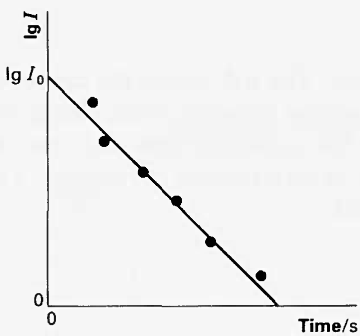


Figure B25
Log–linear plot of decay.

Plotting a graph of the logarithm of the discharge current against time produces a straight line (figure B25 – note that $\lg I = \log_{10} I$). If any quantity is thought to change exponentially, then looking for the constant ratio property or plotting a log–linear graph are useful tests.

QUESTION 43

Streams of charge

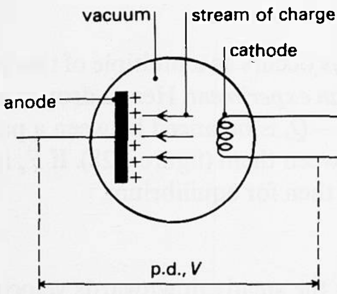


Figure B26
Thermionic emission.

We think that an electric current is due to the motion of small charged particles. We now consider in more detail some of the experiments which lead to the idea that charge can be transferred only in small 'lumps' on these particles. This is the beginning of atomic physics, and eventually brings us to the picture of the atom itself as composed of particles, some of which are electrically charged.

A stream of negative charge can be produced from a metal by heating it (*thermionic emission*) in a vacuum. The charge is accelerated by applying a p.d. between the metal (the *cathode*) and a nearby collecting plate (the *anode*) which is given a positive charge (figure B26). The stream of charge can form a shadow of an obstacle on a fluorescent screen, showing that it travels in a straight line between cathode and anode – figure B27(a).

DEMONSTRATION B21
Electron streams

It can also be deflected by an electric field – set up between two oppositely charged plates positioned either side of the stream, as in figure B27(b), and by a magnetic field – produced either by permanent magnets or a coil carrying a current – figure B27(c). The direction of the deflection in an electric field confirms the view that the stream carries negative charge and that it behaves like a conventional electric current (although no longer trapped inside a wire) whose direction is opposite to that of the velocity of the charge.

The stream can also be shown to heat a target in its path, evidence that it carries energy.

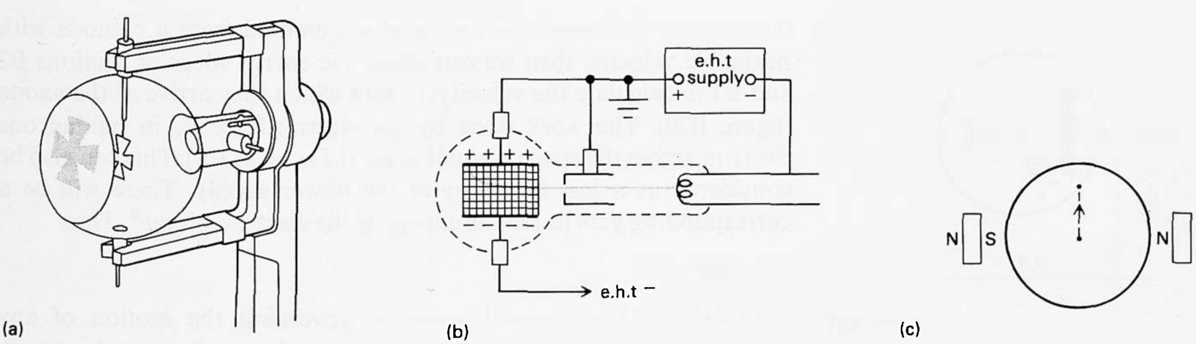


Figure B27
Streams of charge:
(a) forming a shadow;
(b) deflection by an electric field;
(c) upward deflection by a magnetic field (looking into beam).

The elementary unit of charge

EXPERIMENT B22
The Millikan experiment
(charge on an electron)

Experiments on electrolysis of different liquids (not part of this course) show that 1 mole (6.02×10^{23}) of atoms of an element, when ionized, always carries a charge of either $1\times$, $2\times$, $3\times$, or $4 \times 96\,500$ C (the faraday). This suggests that each ion always carries a charge of exactly e, $2e$, $3e$ or $4e$, where

$$e = 96\,500/(6.02 \times 10^{23}) = 1.60 \times 10^{-19}\ \text{C}.$$

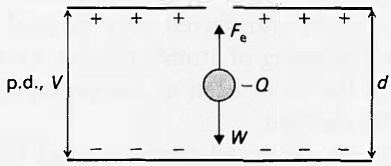


Figure B28
Balancing an oil drop.

The fact that electric charge always occurs as a multiple of this value is shown independently by the *Millikan experiment*. Here a drop of oil of weight W, carrying a small charge of $-Q$, is balanced between a pair of horizontal plates with a p.d. of V between them (figure B28). If F_e is the electrical force upwards on the drop, then for equilibrium

$$F_e = W$$

The weight W is found by measuring the steady downwards velocity of the drop under the action of gravity and air resistance when the p.d. is removed. (A calibration graph, figure B55 on page 131, relates W to this velocity.) F_e is shown from an energy argument to equal QV/d. Hence

QUESTION 48

$$QV/d = W$$

enabling Q, the charge on the drop, to be calculated.

Careful measurements show that the drop always carries a charge equal to a small multiple of e above, 1.60×10^{-19} C.

QUESTION 45

Experiments such as B21 and B22 support the view that negative charge is carried on a very small particle of definite mass (the *electron*) and that all electrons carry the same charge of -1.60×10^{-19} C.

Energy and speed of the electrons in a stream

If electrons of charge e and mass m are emitted from a cathode with negligible velocity, then we can apply the energy ideas of Sections B2 and B3 to calculate the velocity, v, with which they arrive at the anode (figure B29). The work done by the electric force F_e in pulling one electron across the space is equal to eV ($1\ \text{J} = 1\ \text{C} \times 1\ \text{V}$). This can also be considered as a *loss in energy* of the power supply. There will be a corresponding *gain* in kinetic energy of the electron of $\frac{1}{2}mv^2$. Thus

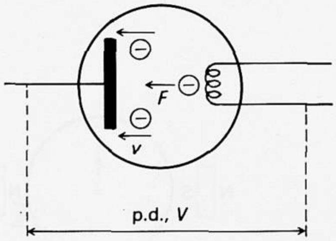


Figure B29
Electrons hitting anode with speed v.

$$eV = \tfrac{1}{2}mv^2$$

This is a fundamental equation governing the motion of any charged particle (in general e becomes ne, where n is a small integer). It will be used particularly in Unit H, 'Magnetic fields and a.c.'

Two points are worth noting about this equation:

i the velocity v $(= \sqrt{2eV/m})$ is independent of the distance between cathode and anode,

ii the velocity only depends upon the **ratio** e/m, the 'specific charge'. (The individual values of e and m are not needed.)

QUESTIONS 46, 47

An important unit of energy used when dealing with atomic-sized particles is the *electronvolt*. If a charge equal to ne is accelerated through a p.d. of V, it gains nV electronvolts of energy.

1 electronvolt (eV) $= 1.60 \times 10^{-19}$ J

It can also be shown that a stream of electrons carries *momentum*. This can be measured by observing the impulse given to a target when electrons are fired in bursts on to it. The way in which the impulse (and hence the momentum transferred) from a given number of electrons depends upon the accelerating p.d. (impulse $\propto \sqrt{V}$) provides confirmation of the view that an electron stream does consist of discrete particles which possess mass as well as charge.

B

READING

APPLICATIONS OF WHEATSTONE BRIDGE CIRCUITS

(Adapted from two articles by C. R. Sawyer and by D. Bridgewater in *Physics at work*. Reproduced by kind permission from BP Educational Service. BP International Ltd.)

Introduction

This part of the *Guide* describes three industrial applications of the Wheatstone bridge circuit:

i the explosimeter
ii the corrosometer
iii a strain gauge pressure transducer.

All rely for their working on the detection of small changes in resistance. In *i* the change is produced by a change in temperature, in *ii* by a change in cross-sectional area, and in *iii* by a change in length and area. (Question 16, on page 142, goes through the relevant theory.)

In two of the examples (*i* and *iii*) the bridge is driven out of balance by the change in resistance: the p.d. produced across the bridge (or the current this p.d. can drive) is taken as an indication of the effect being detected. (Experiment B13 is a laboratory example of this principle.) In the other example (*ii*) the bridge is *restored* to balance, and the change in resistance in one of the arms needed to do this is used as a measure of the effect.

The circuit

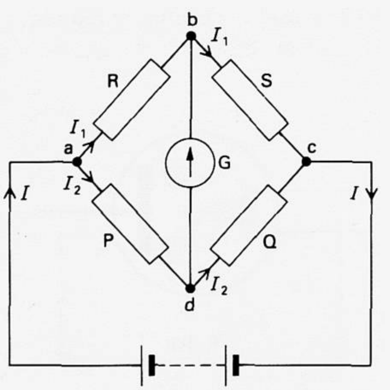


Figure B30
The Wheatstone bridge.

The basic circuit was developed by Professor Sir Charles Wheatstone in 1843, as a method for the accurate measurement of resistance. Four resistors, P, Q, R, and S, are connected as shown in figure B30, to form a bridge or network. A potential difference is applied across ac and a sensitive galvanometer is connected between b and d.

Suppose *R* is the unknown resistance, and *P*, *Q*, and *S* are variable resistances. The current, I, from the battery reaches junction a, where it will divide into currents I_1 through R, and I_2 through P. When I_1 reaches junction b it could divide, and similarly I_2 could divide at junction d. This would provide two opposing currents through G which, if resistors P, Q, and S are adjusted, can be made equal and effectively cancel each other out. No reading would result on the galvanometer and the bridge is said to be balanced. Under these balanced conditions all of I_1 goes through S and all of I_2 goes through Q, and a relationship exists between the four resistors as follows.

Since no current flows through the galvanometer, the potential at b must equal the potential at d. Therefore, the p.d. across R must equal the p.d. across P. Similarly, the p.d. across S must equal the p.d. across Q. That is,

$V_{ab} = V_{ad}$

and

$V_{bc} = V_{dc}$

Since $V = I \times R$, then

$I_1 \times R = I_2 \times P$ [equation 1]

and

$I_1 \times S = I_2 \times Q$ [equation 2]

Dividing equation 1 by equation 2 we have:

$$\frac{I_1 R}{I_1 S} = \frac{I_2 P}{I_2 Q}$$

Therefore:

$$\frac{R}{S} = \frac{P}{Q}$$

If P, Q, and S are known, the unknown resistance R can be calculated.

Applications

i The explosimeter

The explosimeter is a device that measures the concentration of flammable gases and vapours in the atmosphere. It uses the principle that the resistance of a conductor depends upon its temperature. This resistance is not measured directly or even calculated, but the Wheatstone bridge is used as a balanced circuit and it is the imbalance produced by a change in one of the resistances that is actually measured.

The explosimeter depends upon the heat developed by the combustion of an isolated sample of the atmosphere. The sample is drawn into the instrument and passes over a heated filament. Combustibles in the sample burn on the heated filament, so raising its temperature and increasing its resistance. The more combustibles that are present, the higher the temperature that results.

The filament forms one arm of a Wheatstone bridge arrangement which is balanced before any combustible gases are introduced (see figure B31). As the resistance of the filament changes, the balance of the bridge is upset, and a current flows through the meter. The higher the temperature the larger is the current. The reading on the meter scale indicates the concentration of combustible gases or vapours in the sample.

For obvious reasons the combustion of the test sample must be isolated from the atmosphere. To achieve this a metal gauze is used to dissipate the heat. By operating the aspirator bulb, the sample is drawn in through a filter then through the first gauze (the inlet flashback arrester). It passes over the filament before passing out through the outlet flashback arrester and two valves in the aspirator bulb.

The explosimeter is typically used in oil refineries and chemical plants as one means of preventing explosions.

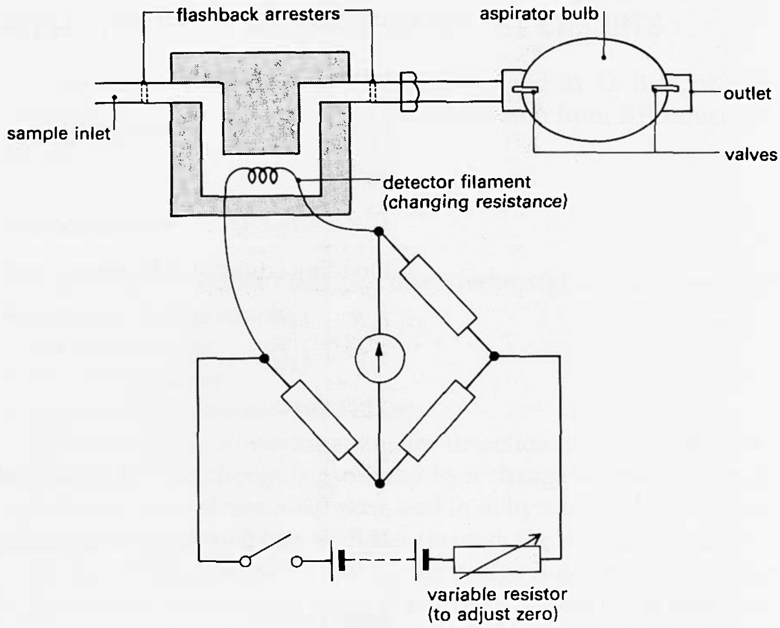


Figure B31
The explosimeter.

ii The corrosometer

The corrosometer is a device that measures the amount and rate of corrosion of metals in any chosen environment. It uses the principle that the resistance of a conductor depends upon its cross-sectional area. Again, the resistance is not measured directly or even calculated, but the imbalance in a Wheatstone bridge circuit produced by a change in one of the resistances determines the amount of corrosion that has occurred.

The corrosometer depends upon the fact that the conductivity of metals is high, while that of the majority of non-metals is negligible. The corrosion of metals produces non-metallic oxides, and so the resistance of the metal increases as the cross-sectional area decreases, because of the corrosion.

A U-shaped piece of wire made from the metal to be tested (the measuring element) projects from the end of a tube – see figure B32(b). One arm of the U is connected to a second piece of the test wire which is sealed inside the tube. This second piece of wire is protected from any corrosive materials throughout the test so that it remains totally unchanged and is called the reference element.

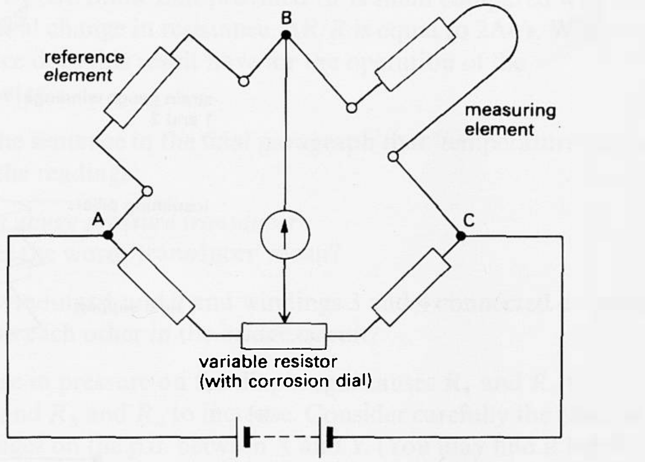
The measuring element, the reference element, and their tube holder are referred to as the probe. The probe is connected to two fixed resistors to form a network as shown in figure B32(a). This is a Wheatstone bridge arrangement, and before any corrosion of the measuring element occurs the variable resistance is adjusted so that no current flows through the meter.

The measuring element of the probe is placed in the corrosive environment. As corrosion proceeds the resistance of the measuring element gradually increases, while that of the reference element remains constant. This upsets the balance of the Wheatstone bridge and allows an ever increasing current to pass through the meter. By adjusting the variable resistor the meter is made to read zero again and the extent of the corrosion is read directly from a scale attached to the variable resistor.

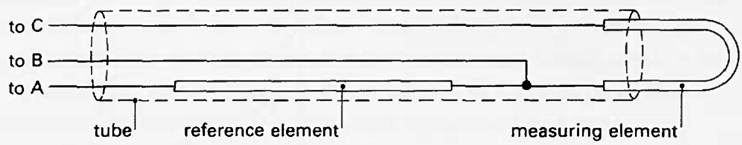
In use the probe is left *in situ* over a long period of time and is only connected to the remainder of the circuit when a reading is to be taken.

Allowance is made in the design for the resistance due to the connecting wires of the probe.

Temperature has no effect on the readings taken as two resistors are in the probe, and the other two in the case, so maintaining a balance.



(a)



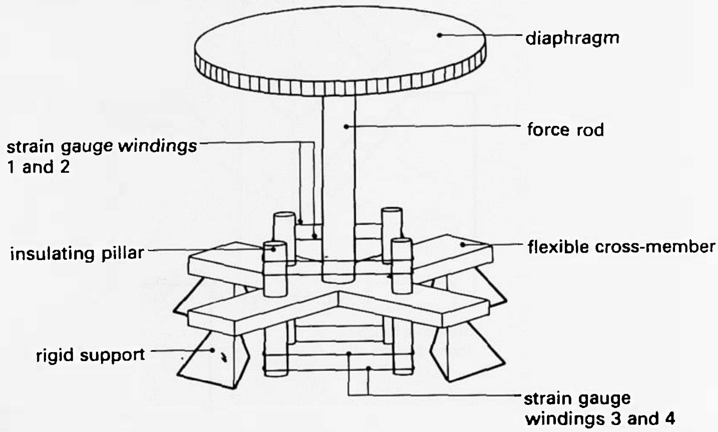
(b)

Figure B32
The corrosometer:
(a) the circuit;
(b) the probe.

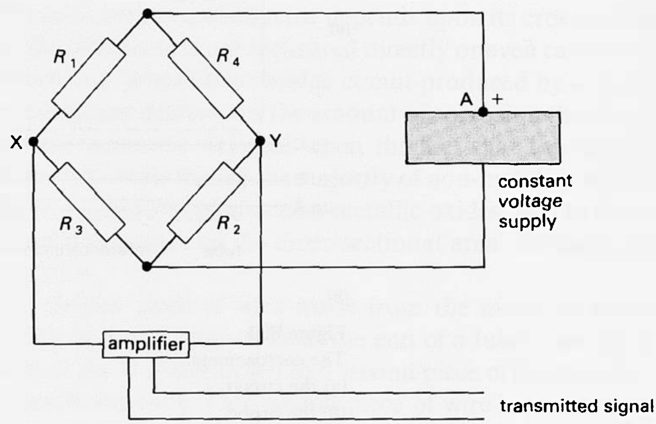
iii The strain gauge pressure transducer

A strain produced in a conductor, usually metallic, causes a change in resistance. It would appear that a strain gauge is most likely to be used for considering structures under stress and indeed it is extensively used for this. However, stress depends on force applied and it is no great step from this to the use of the strain gauge as a pressure transducer. Pressure differences in a fluid flowing through an orifice are related to the velocity of the fluid and so indirectly the strain gauge can be used to measure the rate of flow of a fluid. Figures B33(a) and (b) show the construction of such a pressure gauge and the circuit. Initially the bridge is balanced. Note particularly the significance of the flexible cross-members and the rigid supports, these latter being independent of any changes in pressure.

Suppose the pressure on the diaphragm increased. If windings 1 and 2 were initially under tension they will shorten slightly and likewise windings 3 and 4 will lengthen slightly. The changes in the resistances of these windings will cause the bridge to become unbalanced, resulting in a p.d. occurring between X and Y. This p.d. is amplified and transmitted to a control room. The transmitted signal is a measure of the pressure applied to the diaphragm.



(a)



(b)

Figure B33
Strain gauge pressure transducer.

Questions

The explosimeter

a Discuss how you could in principle set about calibrating the explosimeter, outlining any difficulties you might experience.

b Is the calibration likely to change with usage?

c The flashback arresters are metal gauzes. How do they isolate the test sample from the atmosphere?

d The explosimeter is stated to be one means of preventing explosions. How could it be used in this way?

The corrosometer

e The resistance of a corroded wire is almost entirely that of the pure metal 'core'. Explain how this is consistent with the fact that the oxide coating has a very high resistance.

f A given length of uncorroded wire has a radius r and resistance R. The radius is reduced due to corrosion by an amount Δr and the resistance increases by ΔR. Show that provided Δr is small compared with r, the proportional change in resistance, $\Delta R/R$ is equal to $2\Delta r/r$. What significance does this result have for the operation of the corrosometer?

g Explain the sentence in the final paragraph that 'temperature has no effect on the readings'.

The strain gauge pressure transducer

h What does the word 'transducer' mean?

i Why are windings 1 and 2 and windings 3 and 4 connected diagonally opposite to each other in the bridge circuit?

j An increase in pressure on the diaphragm causes R_1 and R_2 to decrease, and R_3 and R_4 to increase. Consider carefully the effect of these changes on the p.d. between X and Y. (You may find it helpful to regard point A on the constant voltage supply as the positive terminal.)

k Suppose the strain gauge transducer is to be used to monitor a gas pressure in an environment where small changes in pressure are significant. This would mean that the transducer would need to be very sensitive. List and justify those factors in the design of the transducer as shown which you think determine its sensitivity.

l The explosimeter and the corrosometer detected respectively temperature changes and corrosion. What effect would these environmental changes have on the operation of the pressure transducer?

m The p.d. across XY, V_{XY}, can be shown to be proportional to ΔR, the change in resistance of the windings. Ideally V_{XY} should be proportional to the change in pressure Δp applied to the diaphragm (a so-called *linear* transducer), so that $\Delta R \propto \Delta p$. List any features of the design, and any restrictions under which the device would have to operate, which might make this proportionality a reasonable assumption.

LABORATORY NOTES

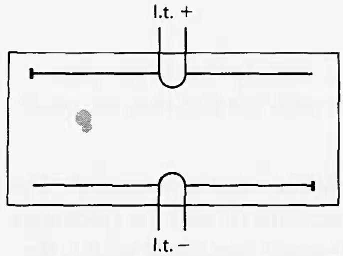


Figure B34
Movement of coloured ions.

DEMONSTRATION
B1 Conduction by coloured salts

Two different crystals are dissolved on to the filter paper. The purple manganate(VII) ion is negatively charged and the deep blue copper ammonium ion is positive. The motion of each ion is tracked by the colour trail left.

Questions

a Which is the conventional current direction?

b How does this relate to the motion of each ion?

c Roughly what value do you estimate for the speed of the ions?

d What happens when the supply terminals are reversed?

e What will happen to each ion when it arrives at the terminal? How will this contribute to the electron flow in the rest of the circuit?

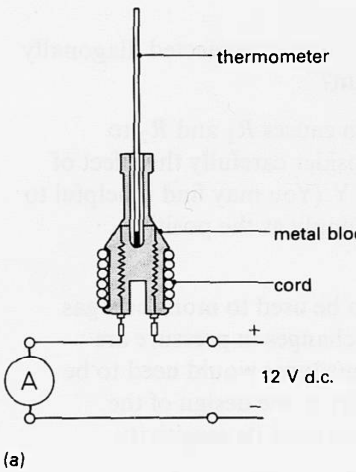
DEMONSTRATION
B2 Measuring p.d. without a voltmeter

apparatus for measuring joules per coulomb
ammeter, 1 A
clock
thermometer, 0–50 °C in 0.2 °C
slotted masses, 1 kg
metre rule
power supply, 12 V
leads

In the first part of the experiment, energy is supplied electrically to the block to raise its temperature by about 10 K. The cord should be wrapped round it 5 or 6 times so that the conditions are as nearly as possible the same as in the second part of the experiment. The current and time are recorded.

In the second part the block is heated by doing work against friction, using the cord as a friction band with a load of about 8 kg – figure B35(b). The temperature rise should be as in the first part.

The relationship *work done = force × distance* can be used to calculate the mechanical energy supplied against friction, using the tension in the cord, the circumference of the block, and the number of turns of the handle.



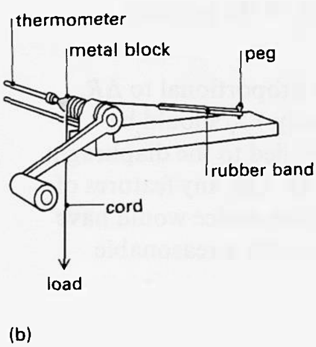


Figure B35
Apparatus for measuring a p.d. without a voltmeter.

Questions

a Why should the temperature rise be kept fairly small?

b The assumption is made that the electrical energy supplied in the first part is equal to the mechanical work done in the second. What features of the experimental method might make this incorrect?

c The second part of the experiment gives the energy supplied; the first part gives the charge passed which will supply this energy. Calculate these two quantities.

d Use the definition of the volt to calculate the applied p.d. in the first part of the experiment. Is this likely to be too high or too low? Check with a voltmeter.

EXPERIMENT
B3 Two-terminal boxes

milliammeter, 100 mA, occasional access to other meter ranges
2 cell holders with four cells
two-terminal boxes
leads
graph paper

B

You may put up to 12 V across the terminals of any box and the current will not exceed 0.1 A (it might be much less). You should investigate as many boxes as possible to see how the current passed depends upon the p.d. applied. Try to make a sensible choice of meter range, always starting with the highest value if you have no idea of the size of the quantity being measured.

Plot your I–V values for each box on a graph.

Questions

a Does the box conduct equally in both directions?

b Does the graph pass through the origin? If it does *not*, what is the significance of the intercept on the V-axis?

c Why might the ratio V/I sensibly be called the *resistance* of the box? Where V/I is constant, calculate it; where it is not constant, decide from the shape of the graph whether the resistance is increasing or decreasing with current.

d From the results of **c**, try to identify the contents of the box.

EXPERIMENT
B4 Comparison of rheostat and potentiometer as controllers

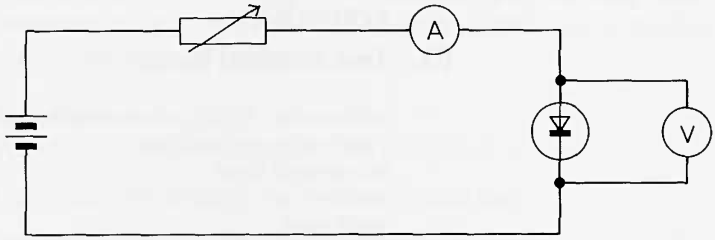
ammeter, 1 A
voltmeter, 10 V
rheostat, 10–15 Ω

diode and clip component holder
and/or
m.e.s. bulb, 2.5 V, 0.3 A, and holder

cell holder with two cells
leads

Set up the circuit as in figure B36(a). You will use either a diode or a lamp. Observe the range of current and p.d. values possible as the rheostat is adjusted from maximum to minimum resistance. Within this range you can make a much finer gradation of changes of I and V than was possible in experiment B3, and you might be asked to take a full set of pairs of readings of I and V.

Now change the circuit to that of figure B36(b). The adjustable component here is called a potentiometer (or potential divider). Note the range of variation of V and I obtainable with this circuit.



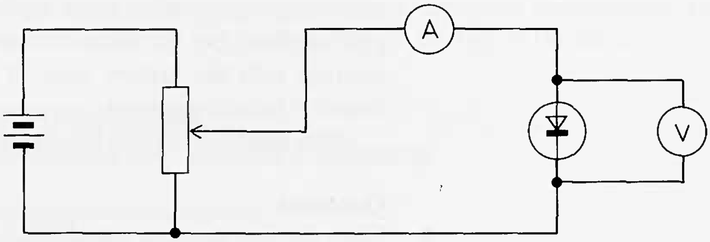


Figure B36
Rheostat and potentiometer as controllers.

Questions

a What determines the range of currents available in the first circuit?

b How does the p.d. obtainable in the second circuit depend upon the position of the sliding contact?

c Both arrangements enable the p.d. across a component to be varied. Compare the possible advantages and disadvantages of one method against the other.

DEMONSTRATION

B5 Effect of size and material on resistance

l.t. variable voltage supply
ammeter, 1 A
voltmeter, 10 V
constantan wire, two different thicknesses
nickel–chromium wire
leads
micrometer

(Covered wire can be used if the insulation is removed at appropriate points.)

A p.d. of 2 V is applied across 0.2 m of the thinner constantan wire and the current noted. The p.d. is then increased in steps of 2 V, the length of wire being increased so as to keep the current the same.

The readings are repeated with the thicker constantan wire. The current need not be the same as in the first part, but should still remain fixed.

Finally, the experiment is done using thin nickel–chromium wire.

Measure the diameters of the wires.

Questions

a How does the resistance of a wire depend upon its length if it has a fixed cross-sectional area?

b Compare the resistances per metre length for constantan and nickel–chromium wires of the same diameter.

c How does the resistance per metre length for two wires of the same material depend upon their diameters? And therefore upon their cross-sectional areas?

B

DEMONSTRATION

B6 Effect of temperature on resistance

Three different conductors are connected in turn into a series circuit with an ammeter or milliammeter and a fixed supply of about 2 V. The conductors are: 3 metres of very thin copper wire (about 2 Ω), a carbon resistor (150 Ω), and a thermistor (a semi-conducting device of normal resistance about 400 Ω).

The copper is screwed into a tight bundle (so that it heats up appreciably when a current is passed); then laid out loosely; and finally put in hot and cold water and cooled by a freezer spray. The other two components are subjected to the same temperature variation.

Since the p.d. is fixed, any changes in current are due to changes in resistance.

Questions

a Do equal changes in current indicate equal changes in resistance?

b Summarize the resistance–temperature behaviour of each component.

c Consider the theoretical relation $I = AvnQ$. You have observed changes in I. Which of the quantities on the righthand side are likely to have changed for each component? Will they have increased or decreased?

EXPERIMENT

B7 Four-terminal boxes

cell holder with four cells
milliammeter, 100 mA
voltmeter, 10 V
four-terminal boxes
leads

Each box has its lower (green) terminals joined by a direct link. There is at least 60 Ω between any other pair of terminals so that a 100 mA meter can be used with a 6 volt supply.

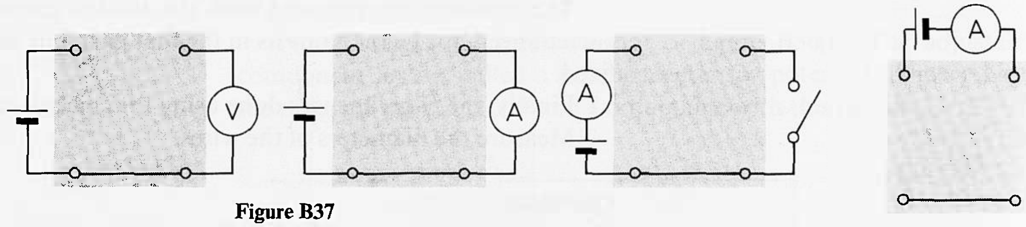


Figure B37
Some circuits which may be used to find out about the boxes.

You should investigate all of boxes **A–D** and at least one from **E–G**. Your teacher might make some harder boxes available to you. Using a voltmeter and ammeter as suggested in figure B37, make appropriate measurements to find out what you can about the circuits inside the boxes.

Question

You might find it useful to work through question 18 in this *Guide* to get an idea of the kind of information you can extract from a measurement, and how the readings can be used to build up a picture of the circuit inside the box.

DEMONSTRATION

B8 Drop in terminal p.d. of source on load

Worcester circuit board kit (3 lamps and 1 cell)
l.t. variable voltage supply
lamp, 12 V, 36 W
lampholder (s.b.c.) on base
e.h.t. power supply
demonstration meter, 10 V d.c., 15 V a.c., and 10 mA d.c.
leads

Using the circuit board, connect the voltmeter across one cell. Then connect first one, then two, and then three lamps in parallel across the cell. Note any changes in p.d. as more current is drawn from the cell.

Repeat the experiment using the 12 V lamp (only use one lamp) both on a.c. and the d.c. supply.

Finally use the e.h.t. supply (under supervision). Set it to 1000 V and connect the milliammeter across the output. Observe both the voltmeter (on the supply) and the milliammeter readings. (Any very high resistance shown as a possible connection on the front panel should not be used.)

Questions

a When you measure the terminal p.d. in the first two parts *with no lamp connected*, what property of the supply are you measuring (at least very nearly)?

b Why does the terminal p.d. drop as more current is drawn?

c From your observations on the e.h.t. supply, roughly what is its internal resistance? Why is it constructed to have this sort of value?

d From casual observations at home (DON'T make any measurements) does the mains supply voltage behave in the same way as the supplies in these experiments? What about the water supply?

EXPERIMENT
B9 Comparison of voltmeters

either
source of e.m.f., 1.5 V, with high internal resistance
or
cell holder with 3 cells
resistor, 10 kΩ *or* resistance substitution box

voltmeter, 5 V or 10 V
voltmeter, same range, low resistance

optional
oscilloscope

leads

You are provided with a source with a fairly high internal resistance. You are going to use different voltmeters to try to measure its e.m.f. List the voltmeters in order of increasing resistance. (For the moving-coil meters you may need to ask what the full-scale current is.)

Connect each voltmeter in turn across the supply, removing one before the next is connected. Start with the meter which you think has the lowest resistance and work your way up. Note each reading.

When the last meter has been connected, add the others again *in reverse order*, but this time do not disconnect one before adding the next (so that at the end you may have three or more meters all connected).

Questions

a Comment on and explain the changing pattern of measured voltage as you increase meter resistance.

b Which of your readings is the best estimate for the e.m.f.?

c Explain the observations in the second part, when you add meters one at a time.

d What other information would you need to be able to estimate the internal resistance of the supply?

DEMONSTRATION
B10 High resistance voltmeter

cell holder with one cell
2 resistors, 220 kΩ
2 clip component holders
voltmeter, 1 V, moving coil
high impedance voltmeter (*e.g.*, digital meter or electrometer/d.c. amplifier)
oscilloscope
leads

B

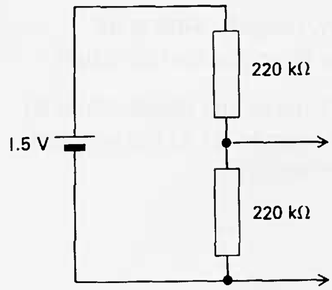


Figure B38

The p.d. across one of the 220 kΩ resistors in the circuit shown in figure B38 is measured using each of the voltmeters in turn: first the moving coil meter, then the oscilloscope, then the digital meter and/or electrometer.

Questions

a Which of the instruments has the biggest loading effect on the circuit? Which has the highest resistance?

b Explain what happens when more than one voltmeter is used at the same time.

c Suggest experiments where it would be important to use a meter which has a negligible loading effect.

EXPERIMENT
B11 Potentiometer balancing an e.m.f.

metre wire potentiometer
l.t. supply (or 2 V accumulator)
cell holder with one cell
voltmeters, 1 V and 10 V
microammeter, 100 μA
leads

Set up the circuit as in figure B39(a). Adjust the position of the sliding contact (do *not* scrape it along the wire) and observe the voltmeter. Compare it with the voltmeter in the second part of experiment B4.

Now connect a cell into the voltmeter circuit as in figure B39(b). You should be able to find a length, *l*, of the wire so that the meter reads zero.

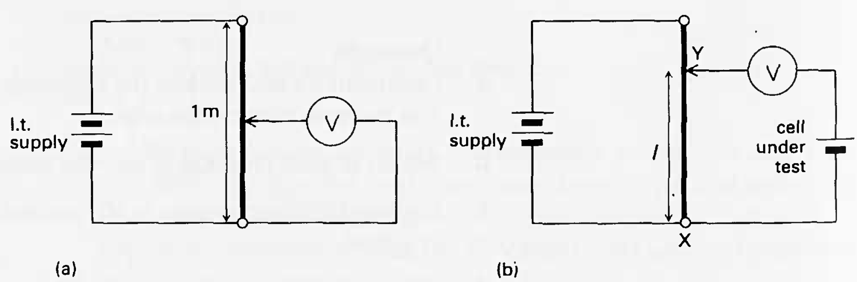


Figure B39
Potentiometer (a) without, and (b) with a balancing e.m.f.

(This is the *balance length*.) When you have found the balance point as accurately as you can, replace the voltmeter with the microammeter. You will find that this arrangement is much more sensitive and you can find the balance point very precisely.

Finally, replace the cell with another apparently similar one. Why does the balance length change slightly?

Questions

a How does the potential difference between points X and Y – figure B39(b) – depend on the length l? What is the potential difference per unit length of wire? Is it constant?

b If the potential at point X is taken to be zero, how does the potential at Y depend on the length l? In which direction must Y be moved for the potential at Y to increase – in the direction of the current or in the opposite direction?

c At balance, what property of the cell does the length l represent?

d State as precisely as you can any differences between the two cells.

EXPERIMENT
B12 Using two potentiometers to make a bridge circuit

Apparatus as for experiment B11, but with a second metre wire potentiometer, and without cell holder and cell

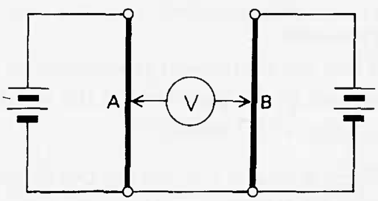


Figure B40
Two potentiometers balanced together.

Join two potentiometers together, as in figure B40. In this experiment the positive terminal of the cell in experiment B11 is replaced by point B on the second potentiometer. Adjust for balance using a voltmeter. Check that a full range of pairs of A–B positions will give balance.

Questions

a State a condition for balance using the word 'potential'.

b When a balanced state has been reached, what might upset it (A and B remain fixed)?

c Suggest a modification to the circuit which would remove the disadvantage of **b**. Make the modification and confirm that you have removed the disadvantage.

d With this change made, replace the voltmeter with a microammeter. Observe what happens to the current through the meter as *small* adjustments are made to the position of B, keeping A fixed. How does the current depend upon the movement of B?

EXPERIMENT
B13 Detection of small resistance changes

cell holder with four cells
thermistor
potentiometer, 1 kΩ or 5 kΩ
resistance substitution box
microammeter, 100 μA
leads

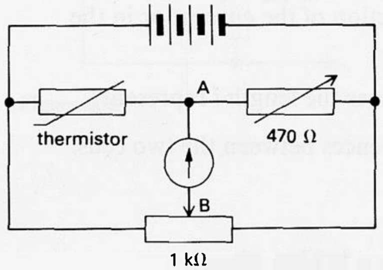


Figure B41
Detecting a small resistance change.

Set up the circuit as in figure B41. It is essentially the same as that for experiment B12, except that there is now only one sliding contact. Adjust the potentiometer until the bridge (the name for this kind of circuit) is balanced.

Demonstration B6 showed that the resistance of the thermistor changes markedly with temperature. This experiment shows how that demonstration can be made more sensitive. Slightly warm or cool the thermistor (gently blow on it, or put on a few drops of a volatile liquid) and observe the bridge move off balance.

Questions

a When the thermistor is warmed its resistance gets less. What will happen to the potential of the junction point between the thermistor and the 470 Ω resistor?

b There is now a p.d. across the meter. Which way will current flow through it? Observe the meter connections carefully (normally current into the red terminal produces a deflection to the right), and check your prediction.

c You have a circuit to detect small resistance changes. Suggest a range of applications for this circuit. How does the out-of-balance current depend upon the change in resistance (see question **d** of experiment B12)?

EXPERIMENT
B14 Capacitors and charge (a series of 8 short experiments)

cell holder with four cells
3 clip component holders
2 electrolytic capacitors, 500 μF
2 electrolytic capacitors, 1000 μF
2 electrolytic capacitors, 2200 μF
oscilloscope
stopwatch
resistance substitution box
2 milliammeters, 10 mA
resistor, 150 Ω
leads

N.B. These experiments use electrolytic capacitors which can be destroyed by connecting them the wrong way round in the circuit. Always check that the + sign on the capacitor is connected nearest to the + terminal of the supply.

B14a *i* Observe the meter deflections when the capacitor is charged and then discharged (broken line). (See figure B42.)
ii What happens if the capacitor is not discharged between two attempts at charging?

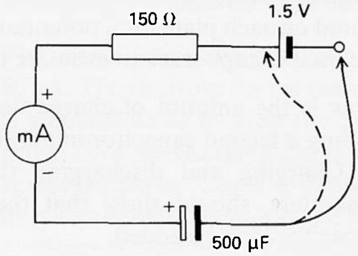


Figure B42

B14b This circuit adds a second meter to the circuit in order to investigate the currents flowing on both sides of the capacitor (figure B43).

What can you deduce about the quantities of electric charge flowing into and out of the capacitor during charge and discharge?

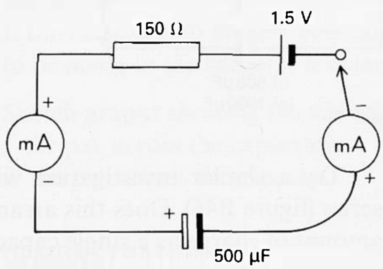


Figure B43

B14c In order to find out precisely how the current in the circuit changes during charge and discharge, an oscilloscope can be used to measure the changing potential difference across a known resistance (figure B44). When using the oscilloscope ensure that:

1 The a.c./d.c. switch is on the d.c. setting.

2 The time-base is initially switched off and the spot is located in the middle of the screen.

3 The *Y*-gain is adjusted so that a p.d. of 1.5 V applied to the oscilloscope causes a vertical deflection of 2 divisions.

i How does the current flowing in the circuit change with time during charge and discharge?

ii Turn the time-base on to the slowest setting and repeat the charge and discharge process.

iii Which quantity on the graph of current against time traced out by the oscilloscope represents the charge flowing around the circuit?

iv How would you calibrate the oscilloscope in order to estimate a value for the charge?

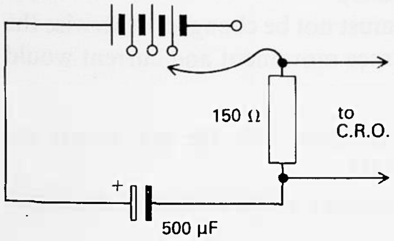


Figure B44

B

B14d Extra cells can be used to give larger pulses. An important deduction can be made by connecting the charging lead successively to the 1.5, 3.0, 4.5, and 6.0 V terminals of the cell holder without discharging between each stage.

B14e Use capacitors of differing value. The capacitor rating is the charge stored on each plate for a potential difference of 1 V. Check this by using the oscilloscope trace to estimate the charge flowing for each capacitor.

B14f How is the amount of charge flowing around the circuit affected by adding a second capacitor in parallel (figure B45)?

Charging and discharging the capacitors as a pair, and then separately, should show that the charges on the plates of the two capacitors can be added.

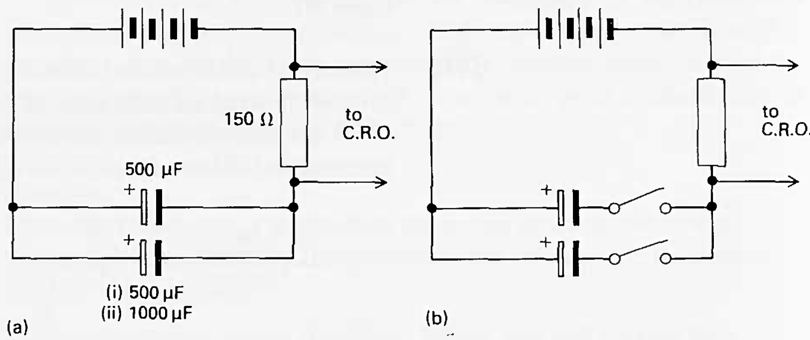


Figure B45

Try a similar investigation with the two capacitors connected in series (figure B46). Does this arrangement store more, less, or the same amount of charge as a single capacitor?

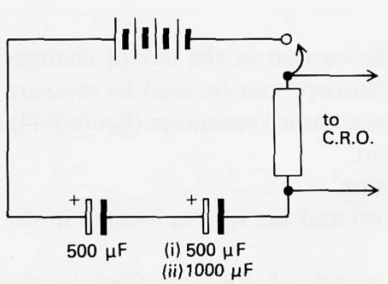


Figure B46

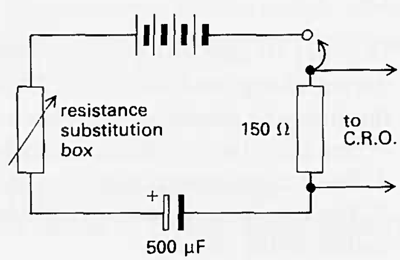


Figure B47

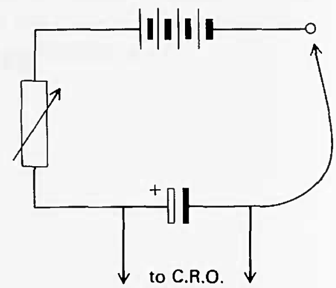


Figure B48

B14g Use a resistance substitution box to investigate the effect of adding extra resistance to the circuit (figure B47).

N.B. The 150 Ω oscilloscope resistor must not be changed, otherwise the constant of proportionality linking trace movement and current would alter.

B14h The oscilloscope can also be used to show how the p.d. across the capacitor changes with time (figure B48).

The 150 Ω resistor is no longer necessary as the current in the circuit is not being measured.

What might you expect to find if the oscilloscope were connected across both the capacitor and resistor? Try it.

DEMONSTRATION
B15 Charging a capacitor at a constant rate

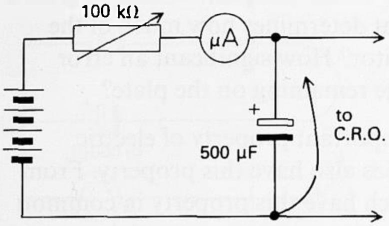


Figure B49
Charging a capacitor at a constant rate.

The capacitor is initially short-circuited and the current adjusted to, say 80 μA. The shorting lead is removed and timing is started. The rheostat is adjusted so as to keep the charging current at its initial value. The progress of the charging can be followed on the oscilloscope as the p.d. across the plates rises. The capacitor is fully charged (*i.e.*, the p.d. across its plates equals the supply p.d.) when the current falls to zero.

Since the current is constant, charge is flowing on to the plates at a steady rate ($80\,\mu C\,s^{-1}$ if the current is 80 μA), and we can find the total charge which has flowed onto one plate and off the other from $Q = It$, where t is the charging time.

If the experiment is repeated for different charging p.d.s V, applied to the same capacitor, we find that $Q \propto V$.

Questions

a If the current is to be kept constant during charging, what change has to be made to the rheostat resistance?

b Sketch graphs showing the variation with time of
i the p.d. across the capacitor.
ii the p.d. across the rheostat.

DEMONSTRATION
B16 Spooning charge

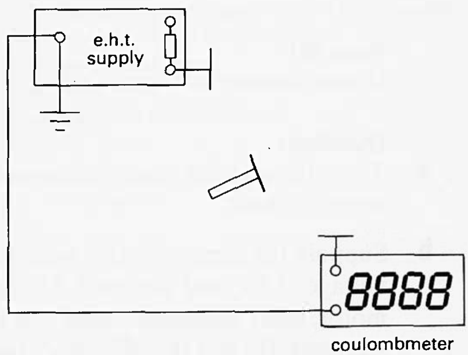


Figure B50
Spooning charge.

N.B. The e.h.t. supply must ***not*** *be connected directly to the coulombmeter input.*

A metal plate with an insulating handle is used to transfer charge from the e.h.t. supply to the coulombmeter, which measures the total charge transferred to it.

The e.h.t. supply is kept constant at, say, 1000 V.

If the same amount of charge is transferred each time, the coulombmeter reading should increase by the same amount for each transfer. How does the amount of charge transferred each time depend on the p.d. of the supply? On the size of the 'spoon'?

Questions

a The coulombmeter measures the p.d. across a capacitor, and so gives a reading proportional to charge. What determines how much of the plate's charge transfers to this capacitor? How significant an error might there be in ignoring any charge remaining on the plate?

b This demonstration brings out an important property of electric charge. Some other physical quantities also have this property. From the following list, pick out those which have this property in common with charge: volume, pressure, energy, temperature, potential difference, mass.

DEMONSTRATION
B17 The energy stored in a charged capacitor (motor)

The capacitor is charged and then discharged through a small motor which raises a load.

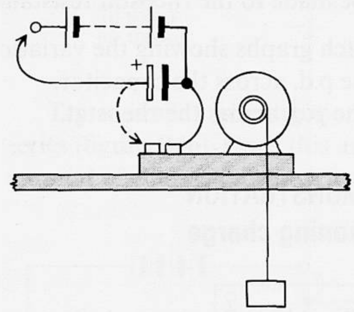


Figure B51
Charged capacitor used to run a motor.

Questions

a Trace through the energy changes in this demonstration, from power supply to load.

b Suppose the demonstration were performed first with a charging voltage of 3 V, and then with 6 V. Ignoring any inefficiency of the motor, what difference would you expect between the two demonstrations? (In fact the efficiency of energy transformation in the motor is low, and this demonstration should be thought of as qualitative only.)

DEMONSTRATION
B18 Energy proportional to V^2 (lighting lamps)

Using the circuit of figure B52(a) the capacitor is charged to 3 V and discharged through the lamp. The brightness and length of flash are noted. The p.d. is doubled to 6 V (circuit (b)) and another lamp added to avoid burning out. The discharge produces brighter and longer flashes than in circuit (a). However, if the capacitor is charged to 6 V and discharged through *four* lamps (circuit (c)), each will flash with the same brightness as the single lamp in circuit (a). At 9 V the capacitor will light three parallel banks of three lamps, each to the same brightness as the single one in circuit (a).

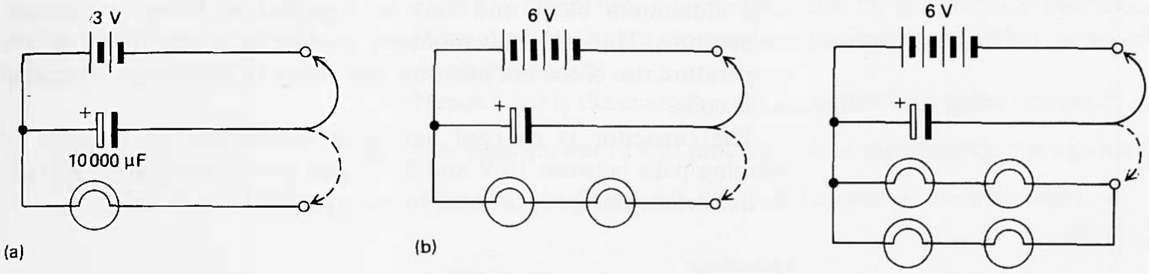


Figure B52
Discharge of capacitor through lamps.

Question

This demonstration shows that the energy stored in a capacitor is proportional to the square of the p.d. across its plates. Using the numerical values above, how many lamps could you light with an 18 V charging p.d. so that each lamp has the same brightness as the original single one?

DEMONSTRATION
B19 Energy proportional to V^2 (heating a coil)

large electrolytic capacitor, 10 000 μF, 30 V
l.t. variable voltage supply *and*
smoothing unit
3 m of insulated constantan wire, 0.4 mm diameter
1 m of copper wire, 0.28 mm diameter
sensitive galvanometer
aluminium block
demonstration meter, 30 V d.c.
leads

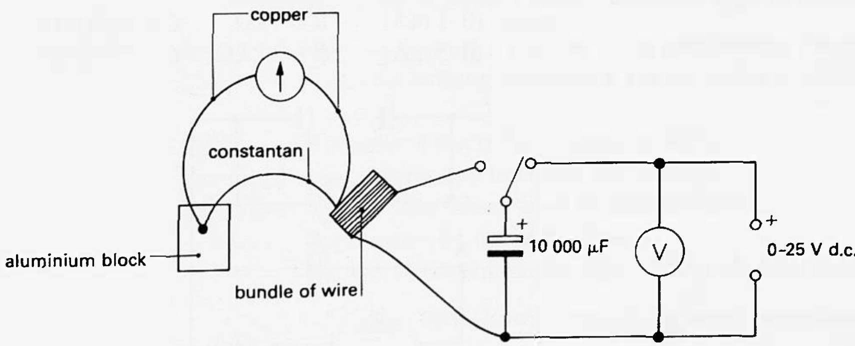


Figure B53
Capacitor discharge through a bundle of wire.

The capacitor is charged to at least 10 V and discharged through the bundle of constantan wire, heating it slightly. The temperature rise is detected by the copper–constantan thermocouple. When a temperature difference is maintained between the two junctions of copper and constantan wires, a small current flows which is proportional to the temperature difference between the junctions. One junction is held in a large aluminium block and may be regarded as being at constant temperature. Thus the galvanometer reading is proportional to the temperature rise of the hot junction, and hence to the energy dissipated in the coil.

The capacitor is charged and then discharged for a range of charging p.d.s between 10 V and 30 V, and the corresponding galvanometer deflections (proportional to energy stored) are noted.

Questions

a Demonstration B18 suggested that the energy stored in the capacitor is proportional to the square of the charging p.d. What graph could you plot to verify this?

b As it stands, this experiment gives a quantity which is *proportional* to the energy dissipated – the galvanometer deflection. What steps *in principle* would be needed to calibrate this deflection in joules?

DEMONSTRATION
B20 Decay of charge

l.t. variable voltage supply
voltmeter, 10 V
capacitor, 500 μF
clip component holder
demonstration meter, 100 μA
resistor, 100 kΩ
leads
stopclock

A 100 μA demonstration meter might not be available. Suitable alternatives are listed here, together with appropriate alternative values for resistance and capacitance.

meter	(0–1 mA)	$R = 5\,\text{k}\Omega$	$C = 10\,000\,\mu\text{F}$
	(0–5 mA)	$R = 2.2\,\text{k}\Omega$	$C = 25\,000\,\mu\text{F}$

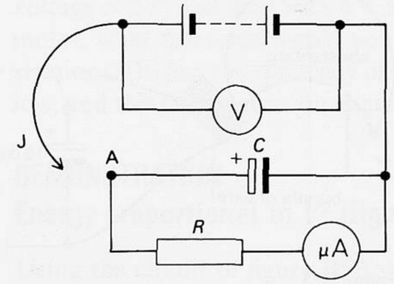


Figure B54
Charge decay circuit.

The capacitor is charged by connecting the flying lead J to A. The discharge is started by removing J from A; timing is started at that instant. The current reading is taken every ten seconds.

Questions

a Suppose the current at any instant is I. What is the p.d. across the resistor? (Either take a numerical value for R or work in symbols.) What must be the p.d. across the capacitor (again, either numerically or algebraically)?
Hence what is the charge on the capacitor for a given current I?

b Use your answer to **a** to plot a graph of capacitor charge against time.

c Why does the charge *not* decay at a constant rate with time?

B

DEMONSTRATION
B21 Electron streams

transformer
e.h.t. power supply
stand for tubes
Maltese cross tube
Perrin tube
deflection tube
pair of coils
gold leaf electroscope
h.t. power supply
battery, 12 V
fine beam tube
Magnadur magnet
rheostat, 10–15 Ω
demonstration meter, 100 mA

Manufacturer's instructions should be followed for the setting up of the tubes.

Safety note: The h.t. power supply is potentially dangerous, so treat it with respect. Always switch it off before making or altering connections to it. It is advisable to use leads having shrouded 4 mm plugs.

A selection of the following demonstrations may be made:

stream of electrons making a shadow of an obstruction (Maltese cross)
stream of electrons coming through a slit to make a splash across a screen
deflection of stream of electrons by electric fields
fine beam tube, raising and lowering gun voltage
deflection of beam (fine beam tube) by electric field
deflection of fine beam by magnetic field
electrons collected to determine the sign of their charge (Perrin tube)

Figure B27 (page 105) shows some of the more important effects to be observed.

Questions

a For each demonstration performed, attempt to answer each of the following questions:

i Is there evidence of a *flow* in the tube?

ii Does it indicate that charge is carried on particles?

iii What does it tell you about the sign of charge carried by the stream?

iv Where there is a deflection, why does the stream bend just the amount that it does?

b (Do this question if you know the relation between the direction of the force on a current in a magnetic field and the directions of current and field.)

Consider the deflection of the beam in a magnetic field. The fact that the magnetic field can move the beam around suggests that the beam is equivalent to a current. Observe the deflection in a field whose direction you know, and decide which is the current direction. What is surprising about this result? How does the result relate to demonstration B1?

OPTIONAL EXPERIMENT

B22 The Millikan experiment (charge on an electron)

Millikan apparatus

either
e.h.t. power supply
or
h.t. power supply
} according to manufacture

multirange meter
leads

Safety note: The h.t. power supply is potentially dangerous, so treat it with respect. Always switch it off before making or altering connections to it. It is advisable to use leads having shrouded 4 mm plugs.

Follow the manufacturer's instructions for the detailed setting up and adjustment. You will need to spend some time familiarizing yourself with the various procedures in this experiment: obtaining oil drops, observing them conveniently, confirming that some are charged, and controlling their fall by varying the applied p.d. so as to balance them.

When a charged drop is balanced the electrical force on it (QV/d) is equal in magnitude to its weight. (Q is the charge on the drop, V the p.d. needed to hold it stationary, and d the spacing of the plates in the instrument.) (See also question **48** on page 158.)

In order to measure the weight of a selected drop, time its fall over a standard distance, with the p.d. turned off. Figure B55 shows a graph of weight against time to fall 1 mm in air, for drops of oil of density $864\,\mathrm{kg\,m^{-3}}$. If the oil you are using has a different density, *multiply* the weight obtained from the graph by $\sqrt{(864/\text{your oil density})}$ to obtain the correct weight.

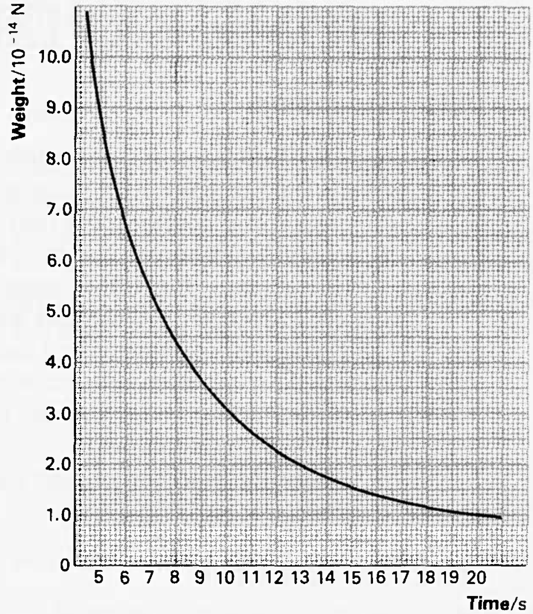


Figure B55
A graph of weight against time for oil drops (density 864 kg m^{-3}) to fall 1 mm in air at 23 °C.

Question

Calculate the charge on a particular drop and repeat the measurement for as many different drops as possible. To what extent do your results show that the charge is always a small multiple of some basic value? Calculate this value and try to put some limits of experimental uncertainty on it.

HOME EXPERIMENTS

BH1 The resistor

'Off-the-shelf' resistors of predetermined values are very inexpensive today, and easily taken for granted. In this practical task you should try to make a 25 Ω resistor using only those materials that you can find in, or around, your house. You should not design your resistor on a 'trial and error' basis, but rather using knowledge of the resistivity of the material which you are working with and its dimensions.

If you use a voltmeter and ammeter to check your design certain factors must be taken into account. What are they? What resistance-measuring device could you use to check your resistor which illuminates these considerations?

Check the precision of your resistor and compare it with others in the class.

BH2 The voltaic pile

In your physics course you use a variety of voltage sources with differing characteristics and limitations. In this task you should attempt to make a 'voltaic pile', able to provide the biggest e.m.f. that you can contrive, though your design should have a volume no bigger than that of a large match box.

The e.m.f. of your voltaic pile is found when 'open circuited', where it is often assumed the voltmeter draws negligible current. Find the p.d. of your design when it provides current through a 500 Ω resistor. Also measure the peak current which flows through the resistor when the circuit is initially closed. You will then be able to find the internal resistance of the pile.

(Warning: Do not try to obtain electrolyte or electrodes by taking a dry cell apart: some modern dry cells contain dangerous materials.)

Tabulate your results and compare them with those obtained by others in the group like this:

Name	e.m.f.	p.d.	Peak current	Internal resistance
B. Mange	1.2 V	0.3 V	0.6×10^{-3} A	1.5×10^{3} Ω
...	...	...	...	...
...	...	...	...	...

Table B1

Study the tabulated results. Can you see any patterns? Perhaps plotting a few rough graphs may help you.

QUESTIONS

Flow

1(L) Think of a tube containing liquid which has a cross-sectional area of one square centimetre (10^{-4} m^2). Suppose the liquid conducts a current of 10^{-2} ampere. For simplicity, think of the current being carried by a lot of charged particles, all moving along at the same speed, v, which you will be able to calculate if some more assumptions are made about the charged particles.

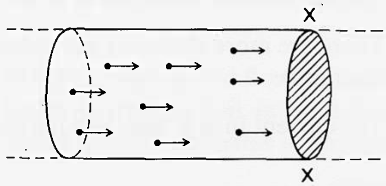


Figure B56

Suppose there is a counting station at XX, which records the number of particles crossing that slice of the tube.

a In 16 seconds, with a current of 10^{-2} ampere, what electric charge passes XX?

b If each particle has a charge of 1.6×10^{-19} coulomb (the magnitude of the charge on an electron), how many particles pass XX in 16 seconds?

c Suppose there are 6×10^{26} charged particles in each cubic metre of liquid. How many charged particles are there in each one-metre length of the tube, if the area of cross-section is 10^{-4} m^2?

d From the answer to **b**, the number of particles crossing XX in 16 seconds, and the answer to **c**, find the length of liquid in the tube behind XX from which all the particles cross XX in 16 seconds. (Of course, this length is 'filled up' again with more particles from behind.) You should have an answer much less than one metre. If not, think again.

e The length in the answer to **d** is also the distance a particle travels in 16 seconds at the unknown velocity v, since it is that velocity which carries it past XX. What is the velocity v? Is this result surprisingly large or small? Is there any evidence that helps you to have confidence in it?

f Now go through questions **a** to **e** above but using I for current, t for the time of flow, Q for the charge on each particle, n for the number of particles in each cubic metre, A for the cross-sectional area of the tube, and v for the velocity. You should get $v = \dfrac{I}{AnQ}$. Why is there no time, t, in this answer?

g For a given current in a given sized tube, what is the effect on v of decreasing the density of charged particles, n? What is the effect of decreasing the charge on each particle, Q? What reasons might be given to support a value of around 10^{26} particles per cubic metre for n? Can you think of a liquid (pure? solution?) in which n might be substantially less than this?

2(P) Figure B57 shows a junction of two pieces of copper wire which form part of a simple series circuit around which a current is flowing. Discuss the accuracy of the following statements.

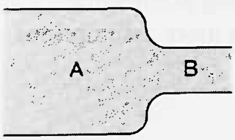


Figure B57

a Charge must be piling up at the junction.

b The conduction electrons in B are moving more slowly than those in A.

c The conduction electrons in B are moving faster than those in A.

d There are more electrons per cubic metre doing the conduction in A than in B.

e The current in B is less than the current in A.

Electrical energy

3(E)a Estimate how much energy is stored in a 1.5 volt 'U2' (D-type) cell.

b Estimate how many joules are needed to set a train in motion.

c Estimate the least time in which a train of mass 500 tonnes could attain a speed of 30 metres per second on level track taking 100 amperes from a 20 000 volt supply.

d An electric train runs at its maximum power of 2.5 MW. What current does it use if it is supplied at
i 2500 V?
ii 25 000 V?
iii If the current in each case runs through supply cables, by what factor would the power wasted in heating the cable be greater for *i* than for *ii*?
iv For the same wastage in the two cases, how much longer might the cable be in case *ii* than in case *i*, assuming the same area of cross-section of cable in each case?

4(R) A lamp B_1 is connected to the terminals X and Y of a battery as shown in figure B58(a).

A second, identical, lamp B_2 is then added to the circuit as shown in figure B58(b). The battery has negligible internal resistance and does not run down.

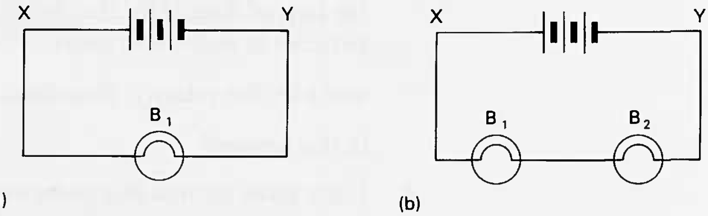


Figure B58

The following are statements about the circuits.

1 The number of joules transformed per second is the same in each circuit

2 The number of joules expended per coulomb by the battery is the same in each circuit

3 The number of coulombs flowing out of the battery per second is the same in each circuit.

Which of the above statements is/are correct?

A 1 only **B** 2 only **C** 3 only
D 1 and 2 only **E** 1 and 3 only

(Coded answer paper, 1971)

5(E)a What current should flow in the heating element of a domestic electric kettle in order to boil, in 5 minutes, the water for making a pot of tea? Make sensible estimates of any quantities you need.

(Short answer paper, 1978, part question)

b A bathroom shower heater is rated at 8 kW. It is fed by cold water at a temperature of 15 °C. If the shower temperature is not to exceed 40 °C:

i What mass flow rate does this requirement represent? Is this an upper or lower limit?

ii What sensors and control actions would have to be part of the system to take account of fluctuations in the water inlet temperature and flow rate?

(Specific heat capacity of water $= 4200 \text{ J kg}^{-1} \text{ K}^{-1}$)

6(E) The two passages below were written by someone who knows something about the ideas involved, but who is confused and puzzled about them.

You are asked to write a short explanation about each. Your explanation should first point out any mistakes, or ambiguities, or important features and then go on to make a more accurate and complete statement to help the author to understand.

a You can't really understand electrical potential difference except by way of a model. If you think of a current as like water pumped round a circuit of pipes, then the potential difference is like the pressure of the pump. It's a bit mysterious; for example, the electrical unit, the volt, is nothing like the unit of pressure (newtons per square metre), but this model is the nearest you can get to saying what it means.

(Long answer paper, 1978)

b Some people think that what they pay the Electricity Board for is electricity; that lights, cookers, and heaters use up electricity. They know that a complete circuit is needed, but imagine more electricity coming in than going out. They have the idea that a power station manufactures electricity which is piped like water along wires. They may find it hard to see how an alternating current supply can 'supply' anything if the current is going backwards and forwards all the time.

(Long answer paper, 1979)

Voltage–current relationships

7(P) Figure B59 shows the results of measurements of the current I through and the potential difference V across four different electrical components, each concealed inside a box having only two terminals. What can be said about the contents of the boxes, using only the information conveyed by the graphs? The graphs are all drawn to the same scale, even though no markings are shown.

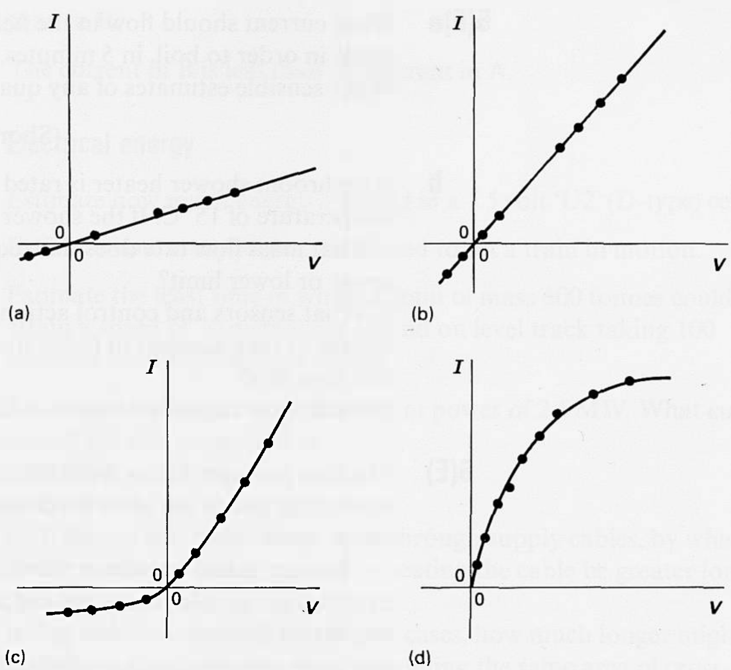


Figure B59

8(P) Here are some values of the potential difference V across a device, and the resulting current I through the device.

V in volts	0	50	100	150	200	250
I in amps	0	0.18	0.25	0.31	0.36	0.40

Which one of the relationships **A** to **E** agrees best with these results?

A $V=kI$ **B** $V=kI^2$ **C** $V=kI^3$
D $V=k/I$ **E** $V=k/I^2$

(Coded answer paper, 1982)

9(E) Part **a** of this question is about interpreting graphs, which is a useful thing to be able to do. Part **b** is about making graphs to test a suggested rule. Part **c** is more philosophical, and considers when it is reasonable to discuss laws and whether they need always be true.

Here is a statement of Ohm's Law.

'The current between two points in a conductor is proportional to the potential difference between these points, provided that physical conditions such as temperature remain constant.'

a Which of the graphs of experimental results in figure B60 could be taken as agreeing with the Law as stated?

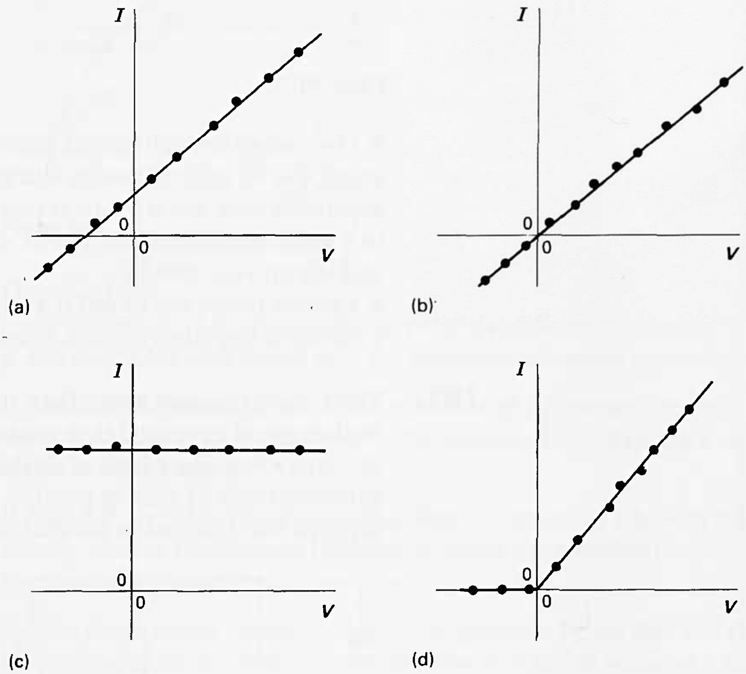


Figure B60

Current/mA	Potential difference/V
1.0	14.5
1.5	21.8
2.0	29.0
2.5	36.2
3.0	43.5
3.5	50.7
4.0	58.0

Table B2

b Table B2 gives some results taken for a sample of a new material. Does the relation between current and potential difference agree with Ohm's Law?

Can you think of any other ways, apart from the one you used, to make this test? What is the resistance of the sample when the current is 2.0 mA? Is the resistance the same when the current is 4.0 mA?

c There are materials (thyrite, metrosil) for which the current–p.d. graph is curved as in figure B61, even though they do not become hot during the experiment. In the light of this fact and of what you already know, what do you think of the following statements?

1 Ohm's Law, as stated, is a false law, as there are exceptions to it. The Law should be rejected.

2 Ohm's Law is a useful summary of the behaviour of some materials, but not all.

3 There are materials that do not obey Ohm's Law, and it would be best to keep the word 'conductor' only for those that do. Then the Law would always be true.

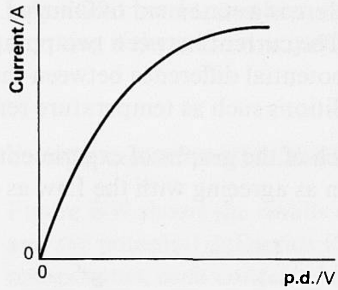


Figure B61

4 Over small enough ranges of current, even a curved current–p.d. graph will be approximately straight. So it would be better to say that, experimentally, Ohm's Law is true over small ranges of current only, to a good approximation. (Look at figures B60(a) and (b) before making up your mind.)
5 I would prefer not to call it a 'law' but to keep that word for statements that always work exactly.

10(L) Thick wires conduct better than thin ones. Because a thick wire could be thought of as several thin ones side by side, it is useful to begin thinking about the effects of thickness by considering resistors connected side by side, in parallel. A p.d. of 12 volts drives current through two resistors in parallel as in figure B62.

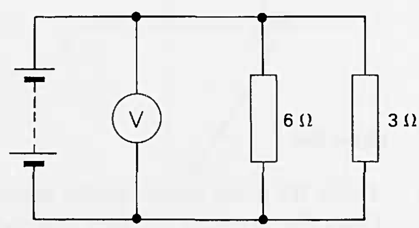


Figure B62

a What current goes through the 6 Ω resistor?

b What current goes through the 3 Ω resistor?

c What is the total current taken from the battery?

d If the two resistors were replaced by a single resistor, which conducts the same current as the total through the 6 Ω and the 3 Ω resistors together, what would be its resistance?

e Now try repeating **a–d** algebraically. Let the p.d. be V and the two resistors R_1 and R_2. If the parallel combination can be replaced by a single resistor, R, you should end up with the useful result

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

11(P) The graph in figure B63 shows the relationship between the current and the potential difference for two different conductors A and B.

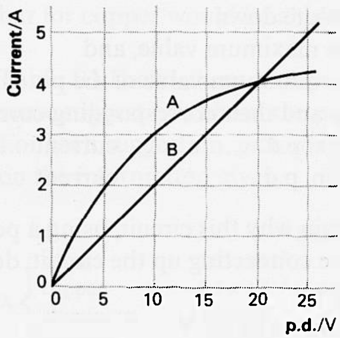


Figure B63

a Describe how
i the resistance of A varies with the potential difference across it.
ii the resistance of B varies with the potential difference across it.

b If A and B are joined in series and a current of 2 A passes through them, what is the total resistance of the combination? Explain how you arrive at your answer.

c If A and B are joined in parallel and draw a current of 3 A from the supply, what is the potential difference across the combination? Explain how you arrive at your answer.

d Within the range of values shown on the graph in figure B63 will the *lowest* resistance of a *parallel* combination of A and B occur at a high value or at a low value of the potential difference across the combination? Explain your reasoning.

(Short answer paper, 1974)

12(E) This question is to be done as an experiment: detailed instructions on carrying it out will be given to you.

The circuit shown in figure B64 has been set up using a 3.0 V power supply, in an attempt to measure the resistance of the lamp at different values of potential difference, varying from 0.2 V to 2.8 V as measured by the voltmeter.

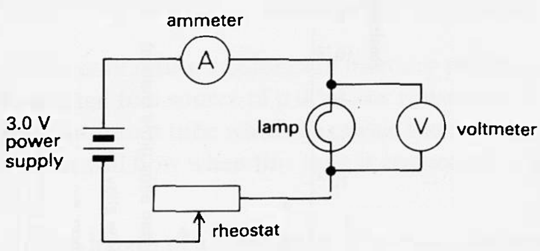


Figure B64

B

a Switch on the supply, adjust the rheostat, and note that the required range of potential differences *cannot* in fact be achieved.

(Do not make any other changes to the circuit.)

Write down

1 the maximum value, and

2 the minimum value of the potential difference obtainable across the lamp and their corresponding currents and lamp resistances.

i Max. p.d. .... current .... lamp resistance ....

ii Min. p.d. .... current .... lamp resistance ....

b Explain why this circuit, using a power supply which was set to 3.0 V before connecting up the circuit, does not enable the p.d. across the lamp to:

i go down to 0.2 V

ii go up to 2.8 V

c Estimate a value for the maximum resistance of the rheostat and show how you arrive at your estimate.

(Practical problems paper, 1982)

Resistivity

13(L) Figure B65 shows the electrical resistivity of a number of materials, and whether the resistivity rises or falls with a rise in temperature. The height of each bar represents the resistivity.

a Notice that the scale is a peculiar one, with equal *multiples* of resistivity spaced out evenly along it. The difference in the height of the bars for silicon and germanium is roughly the same as the difference between those for germanium and carbon. What can you say about the relative sizes of the resistivities of carbon, germanium, and silicon?

b Suppose the printer had not put 10^{-6}, 10^{-3}, 1, 10^{3}, 10^{6}, etc., along the scale but had printed the powers -6, -3, 0, 3, 6, and so on, instead. What quantity would now be plotted on the vertical scale?

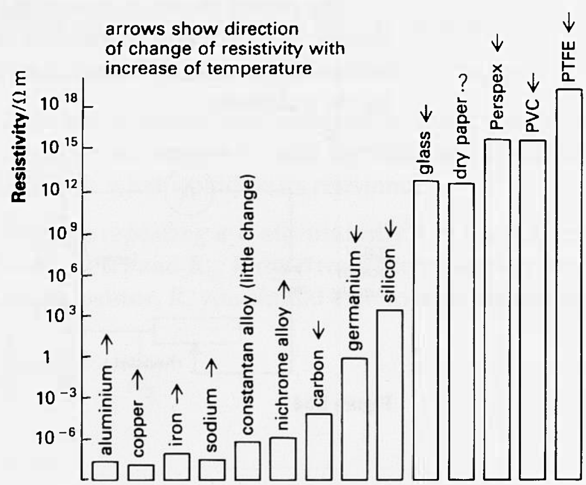


Figure B65

c Estimate roughly how high the bar for PTFE – poly(tetrafluoroethene) – would be if the scale were conventional, with each millimetre representing an increase of resistivity of 10^{-8} ohm metre (so that the bar for copper would be about 1 mm high).

14(E) Table B3 shows three groups of materials, X, Y, and Z. There follow some suggestions about the possible nature or uses of such materials. For each suggestion, pick the group or groups to which it *might* apply, on the information given.

Group	Material	Resistivity at 20°C/Ω m	
X	silver	1.6×10^{-8}	all increase with rise in temperature
	copper	1.7×10^{-8}	
	aluminium	2.7×10^{-8}	
	mercury	69×10^{-8}	
Y	graphite	$350–6500 \times 10^{-8}$	all decrease with rise in temperature
	germanium	0.47	
	silicon	2.3×10^{3}	
Z	Pyrex glass	10^{12}	all decrease with rise in temperature
	paraffin wax	10^{14}	
	polystyrene	10^{15}	

Table B3

a They contain many electrons which are free to move.

b Practically no charged particles at all are free to move.

c When it becomes hotter, increased atomic vibrations somehow free more charged particles so that they can move.

d When it becomes hotter, increased atomic vibrations somehow get in the way of moving charge and obstruct its flow.

e The number of charge carriers free to move is much less than for a metal, but is more than for a typical 'insulator'.

f Some might be useful as the wrapping for a submarine cable.

g A piece the size of a pea will pass a current between 10 μA and 10 mA under a p.d. of one volt (one of the group might pass more).

h Electrical properties would be significantly affected by surface moisture.

i Some could be used to make high-current shunts for meters.

15(P)a A tube containing a column of mercury passes a current of 0.1 A when connected to a source of p.d. of low resistance. If all of this mercury is now put into a tube which has twice the radius of the first tube, what current will flow when this tube is connected to the same source of p.d.?

b A given length of a conductor, of rectangular cross-section, has a resistance R. If every linear dimension were halved what would the new resistance be? What relevance might this result have to the problem of putting resistors on to microchip circuits?

B

16(L) This question is about the way the resistance of a wire changes when it is stretched. If the wire has resistivity ρ, length l, and radius r, then its resistance, R, will be given by

$$R = \frac{\rho l}{\pi r^2}$$

If it is stretched, l will increase, and also r decreases: both of these factors will increase the resistance.

a This part of the question calculates an approximate expression for the increase in resistance, δR, caused by increases in length, δl, and in radius, δr. From the formula above, we can write the new resistance as

$$R + \delta R = \frac{\rho}{\pi}\left(\frac{l + \delta l}{(r + \delta r)^2}\right)$$

If $\delta r \ll r$ (so that $(\delta r)^2$ can be neglected in comparison with r^2), show that δR is approximately equal to

$$\frac{\rho}{\pi}\left(\frac{r\delta l - 2l\delta r}{r^3}\right)$$

b This rather complicated result can fortunately be simplified if we think about *proportional* changes. If we divide the expression in **a** by R, we shall obtain the fractional increase in R, $\delta R/R$. Show that

$$\frac{\delta R}{R} = \frac{\delta l}{l} - 2\frac{\delta r}{r}$$

What is the connection between this formula for fractional changes and the original formula for R? (Hint: look at the powers of l and r in the formula.)

c For many metals the ratio $\left(\frac{-\delta r/r}{\delta l/l}\right)$ is constant and equal to about $\frac{1}{3}$. (This fraction is called Poisson's ratio; it varies somewhat from one material to another. Note the negative sign, indicating a reduction in radius when stretched.) Show that for a constantan wire, with a Poisson's ratio of $\frac{1}{3}$,

$$\frac{\delta R}{R} = \frac{5}{3}\left(\frac{\delta l}{l}\right)$$

A constantan wire of resistance 500 Ω is subjected to a strain of 1 %. By how much does its resistance change?

d A wire used in this way is called a *strain gauge*. What useful property for measurement purposes does the formula in part **c** show? The reading in this *Guide*, pages 111 and 112, describes one important application of strain gauges.

17(L) In question **1** you showed that if a current I flows through a conductor of cross-section A, in which there are n carriers per cubic metre, the velocity v of the drift of carriers with charge Q is:

$$v = \frac{I}{AnQ} = \frac{I}{A} \times \frac{1}{nQ}$$

(I/A is often called the 'current density'.)

a If a length of wire has a resistance R, and there is a p.d. V across it, then

$$I = V/R$$

Write an equation for I/A in terms of V, R, and A.

b If the length of the wire is l, and the resistivity of the material is ρ, then the resistance is

$$R = \frac{\rho l}{A}$$

Write a new expression for I/A without R in it. (*Check*: A should have vanished.)

c In a wire of copper, resistivity 1.7×10^{-8} ohm metre, when there is a potential difference of, say, 10 volts across 10 metres of wire (1 volt per metre), what is the current density in amperes per square metre?

Check: this seems big, doesn't it? What is the current through a wire of cross-sectional area 1 mm^2 at this current density?

Do you think that a piece of copper is often arranged in a circuit with 1 volt per metre across it?

d As was said above, the carrier velocity v is, on average

$$v = \frac{I}{A} \times \frac{1}{nQ}$$

You now have a value for I/A. Assuming that the carriers in copper are electrons, use $Q = 1.6 \times 10^{-19}$ coulomb, to find the value of the constant in

$$v = \frac{\text{constant}}{n}$$

when the wire has 1 volt per metre across it.

e Suppose that there is just one conduction electron for each copper atom (a very risky guess). Then n is the same as the number of atoms in a cubic metre of copper.

Calculate the value of n from these data:

1 1 cubic metre of copper has a mass of 9.0×10^3 kg.

2 53.5 kg of copper contain 6.0×10^{26} copper atoms.

f Now find the average drift velocity, v, of the electrons in metres per second, combining the answers to **d** and **e**.

B

Circuits and meters

18(P)a–e In the figures below, A, B, C, and D are four terminals of a box containing resistors connected between the terminals. The resistors are not shown, being inside the box and not visible. All the resistors have constant resistance and there are no diodes, lamps, or other components with non-linear characteristics. The terminals C and D are joined by a wire of low resistance, as shown. The battery has a potential difference of 6 V and has negligible resistance.

Say what you can about the contents of the box as a result of each test shown in figures B66(a) to (e).

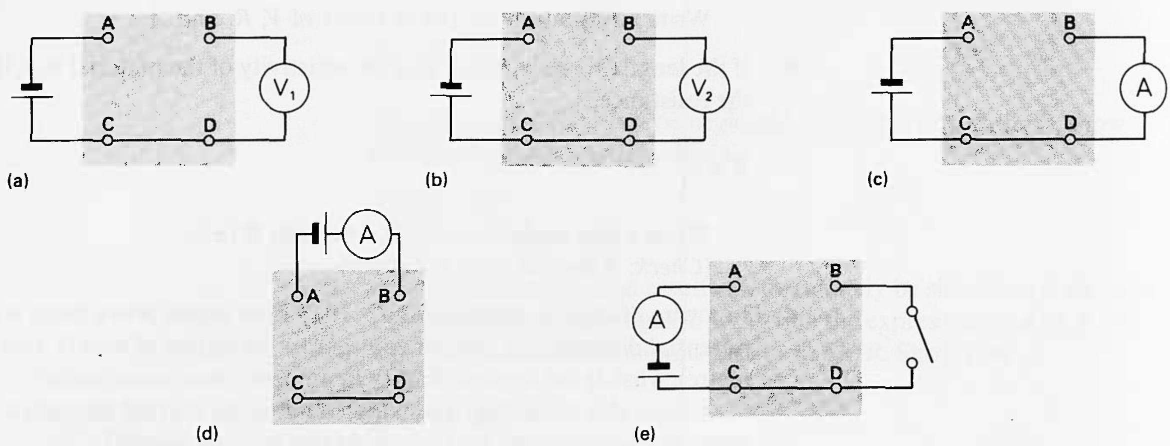


Figure B66

a V_1, a high-resistance voltmeter, reads 6 V. (Figure B66(a).)

b V_2, a voltmeter of resistance 1000 Ω, reads 4.5 V. (Figure B66(b).)

c A is a milliameter, and reads 18 mA. (Figure B66(c).)

d A again reads 18 mA. (Figure B66(d).)

e When the switch is open, A reads zero. (Figure B66(e).) When it is closed, A reads 18 mA again.

Taken together, what do all these tests suggest might be the circuit inside the box?

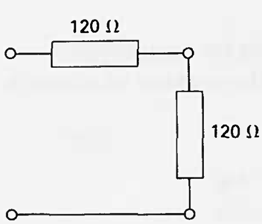


Figure B67

19(R) Two 120 ohm resistors are connected as shown in figure B67 between four terminals. In the circuits of figure B68 (a) to (e), this network is connected to a 6 volt battery of negligible internal resistance. In circuits (a) and (b), a very high resistance voltmeter is shown connected in two ways to the circuit. In circuits (c), (d), and (e), an ammeter of very low resistance is shown connected in three ways to the circuit.

Beside each meter is written a prediction of its reading, which may or may not be correct.

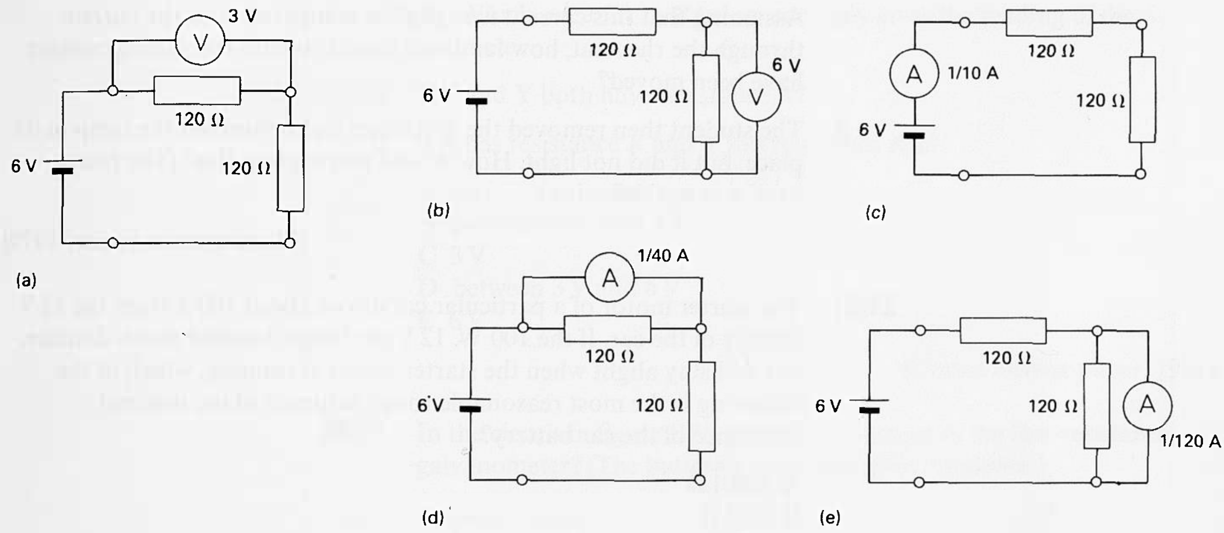


Figure B68

a Which one prediction is correct?

b Which one prediction is just twice as large as it should be?

(Coded answer paper, 1979)

20(R) A student wanted to light a lamp labelled 3 V, 0.2 A, but only had available a 12 V battery of negligible internal resistance. In order to reduce the battery voltage the student connected up the circuit shown in figure B69(a). The student included the voltmeter – using it rather stupidly – so that the voltage could be checked before connecting the lamp between A and B. The maximum value of the resistance of the rheostat at CD was 1000 Ω.

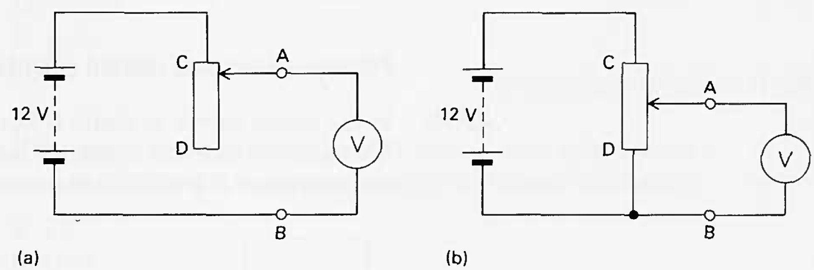


Figure B69

a The student found that, when the sliding contact of the rheostat was moved down from C to D, the voltmeter reading dropped from 12 V to 11 V. What was the resistance of the voltmeter?

b The student modified the circuit as shown in figure B69(b), using the rheostat as a potentiometer, and was now able to adjust the rheostat to give a meter reading of 3 V. What current would now flow through the voltmeter?

c Assuming that this current is negligible compared with the current through the rheostat, how far down from C would the sliding contact have been moved?

d The student then removed the voltmeter and connected the lamp in its place, but it did not light. How would you explain this? (The lamp itself was not defective.)

(Short answer paper, 1979)

21(E) The starter motor of a particular car draws about 100 A from the 12 V battery of the car. If the 100 W, 12 V car lamps become much dimmer, but still stay alight when the starter motor is running, which of the following is the most reasonable rough estimate of the internal resistance of the car battery?

A 0.001 Ω
B 0.05 Ω
C 0.5 Ω
D 5 Ω
E 100 Ω

(Coded answer paper, 1977)

22(P) The p.d. across the output terminals of a source of electrical energy connected to a variable resistor was measured for different values of current as the resistance, R, was varied. The following results were obtained:

p.d./V	10	9	8	7	6	5	4	3	2	1
current/A	0	1	2	3	4	5	6	7	8	9

What is the internal resistance of the source? Plot a graph of the resistance in the external circuit (R) against the output power as ordinate. What general conclusion do you draw from the graph?

Potentiometers and related circuits

23(R) In the circuit shown in figure B70, resistors X and Y are connected to a 6 V battery which has negligible internal resistance. A voltmeter which has resistance R is connected across Y.

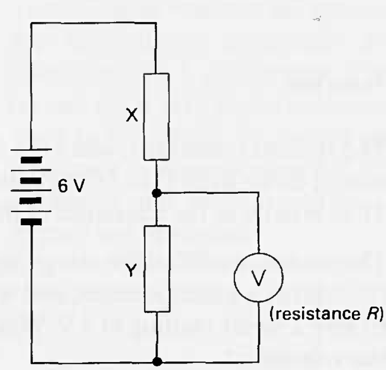


Figure B70

Which one of A to E below correctly gives the reading of the voltmeter

a if X and Y both have resistance R?

b if X has resistance R and Y has resistance $R/2$?

A zero
B between zero and 3 V
C 3 V
D between 3 V and 6 V
E 6 V

(Coded answer paper, 1981)

24(P) In the circuit in figure B71, what is the current in the low-resistance galvanometer? (The batteries have negligible resistance.)

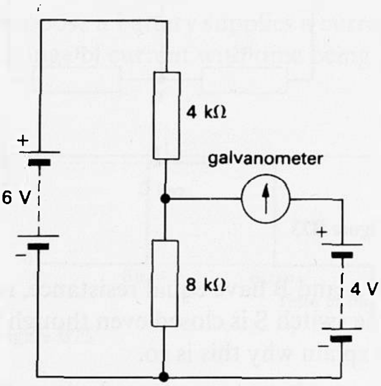
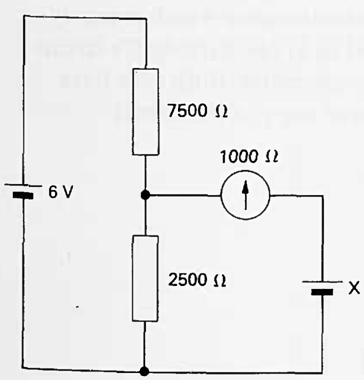


Figure B71

A 2 mA
B 1 mA
C 0.5 mA
D 0.4 mA
E zero

(Coded answer paper, 1980)

25(P) If the meter in the circuit (figure B72) reads zero, what is the e.m.f. of battery X? (The 6 V battery has negligible internal resistance.)



A 2 V
B $1\frac{13}{17}$ V
C $1\frac{1}{2}$ V
D $\frac{4}{5}$ V
E $\frac{4}{7}$ V

(Coded answer paper, 1979)

Figure B72

26(R) Two resistance wires, A and B, made of different materials, are connected into a circuit with identical resistors R_1 and R_2 ($R_1 = R_2$), a sensitive high-resistance galvanometer G, a cell C, and a switch S, as shown in figure B73.

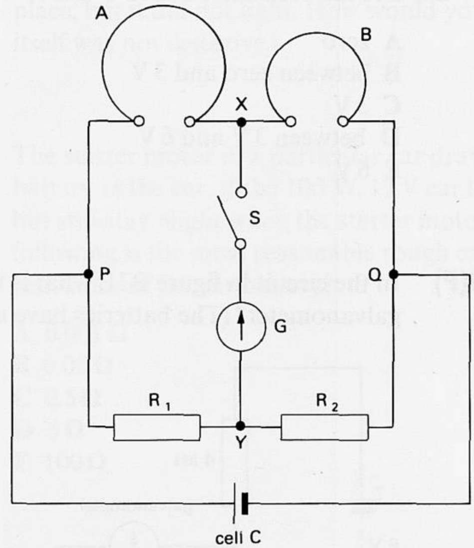


Figure B73

a If A and B have equal resistance, no current will flow through G when the switch S is closed even though the cell is still delivering a current. Explain why this is so.

b The diameter of A is twice that of B and the resistivity of the material of which B is made is $6 \times 10^{-6}\ \Omega\,\mathrm{m}$. It is found that for zero current through G the length of A has to be three times that of B. Calculate, showing your working, the resistivity of the material of which A is made.

c If the length of wire B is now reduced by a small amount so that the current through G is no longer zero, say which way the current will flow through G and explain why.

(Short answer paper, 1981)

27(L) The circuit (figure B74) shows a 4 kΩ potentiometer which is nearly balanced with a 1.5 V cell. You are asked to apply Kirchhoff's circuit laws to find the current through the galvanometer. Both cells have negligible internal resistance. Draw a large copy of the circuit.

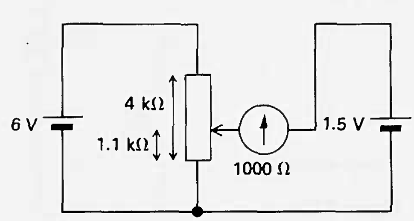


Figure B74

a Decide which way the current flows through the meter (think of the potential at the sliding contact). Mark it in on your circuit.

b Suppose the current drawn from the 6 V supply is I_1, and the galvanometer current is I_2. What current flows in the part of the potentiometer below the sliding contact?

c Kirchhoff's Second Law refers to complete loops in a network. How many loops can you identify in the circuit? How many do you need to find the two unknown currents I_1 and I_2?

d Apply the Second Law to as many loops as you need to produce equations containing I_1 and I_2. Eliminate I_1 from them to find the galvanometer current I_2.

Charge and capacitors

28(I) Suppose a battery supplies a current of two amperes for 10 hours, the change of current with time being shown in figure B75.

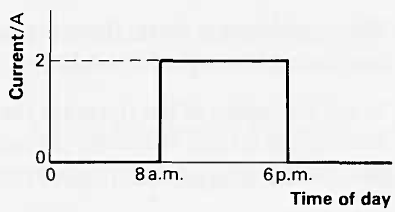


Figure B75

a Describe how the current changes with time.

b What quantity of electric charge flows past each place in the circuit every second during the ten hour period?

c What is the total amount of charge which has flowed around the circuit during the ten hour period?

d Copy figure B75 and show how the charge which has passed from 8 a.m. to some time before 6 p.m. can be represented on the graph.

e A damaged battery produces a graph of current against time like that in figure B76. Show how the charge passed can be represented on the graph as in part **d**.

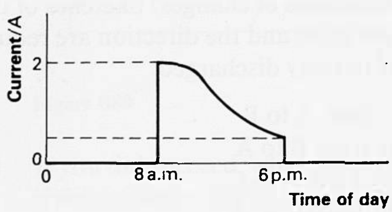


Figure B76

f Estimate the amount of charge which flowed around the circuit.

29(R) This question is about the circuit in figure B77.

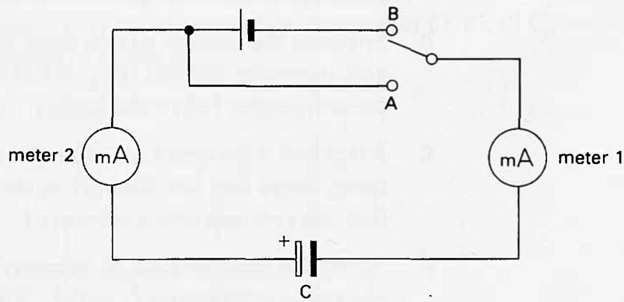


Figure B77

a When the switch is moved from A to B, meter 1 moves momentarily 5 divisions to the right and returns to zero. Which way and by how much will meter 2 move?

b When the switch is moved back to A, how do the pointers on the meters move?

c What evidence is there, from the meter readings, that no charge is conducted through the insulation of the capacitor?

d Mark on copies of the diagram the direction of the current flow around the circuit when the capacitor is charging (switch in position B) and discharging (switch in position A).

e What is the evidence that the charges on the plates of the capacitor are equal in size but opposite in sign?

30(P) When the flying lead is moved from point A to point B in figure B78, the trace on the oscilloscope is as shown in figure B79.

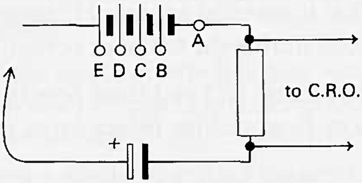


Figure B78

Figure B79

What will be seen on the screen of the oscilloscope in the following sequences of changes? Sketches of the traces indicating the height of the pulse and the direction are required for each change. The capacitor is initially discharged.

a *i* from A to B
ii from B to A
iii from A to C
iv from C to A
v from A to E
vi from E to A

b *i* from A to B
ii from B to C
iii from C to D
iv from D to E
v from E to A

c How do the observations made during sequence **b** lead to the conclusion that the charge on the capacitor, Q, is proportional to the p.d., V, across the plates?

31(L) A constant current of 1 mA flows for 100 s onto one plate of an uncharged capacitor connected to a battery in a circuit. At the end of this time the p.d. across the capacitor is found to be 10 V.

a What current flows off the other plate of the capacitor?

b What is the charge on one plate after 100 s?

c How many coulombs are needed on one plate to give a p.d. of 1 V?

d What is the capacitance of the capacitor?

e If the plates of the fully charged capacitor were allowed to touch, what would now be the total charge on the plates?

32(P) A 100 μF capacitor is charged to 10 V.

a How much charge is there on one plate of the capacitor?

b The charging of the capacitor could be thought of as the removal of electrons from the positive plate and the transfer of the same number of electrons by the battery to the negatively charged plate. How many electrons have moved around the circuit in charging the capacitor? (Charge on the electron, $e = -1.60 \times 10^{-19}$ C.)

c The capacitor is then discharged through a variable resistor – figure B80(a). Describe how you would have to vary its resistance in order to obtain a discharging graph like the one in figure B80(b).

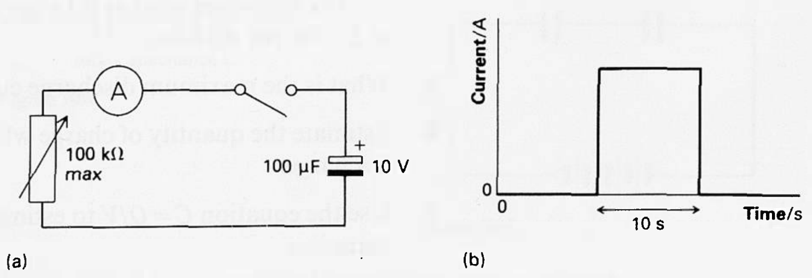


Figure B80

d If you did succeed, what would be the value of the discharging current if the capacitor ended up uncharged?

e Sketch a graph of how the potential difference across the plates of the capacitor changes during the ten seconds discharge time.

33(R) A teacher is given a box of unmarked capacitors. In order to try to find their approximate values, the teacher constructs the circuit shown in figure B81(a).

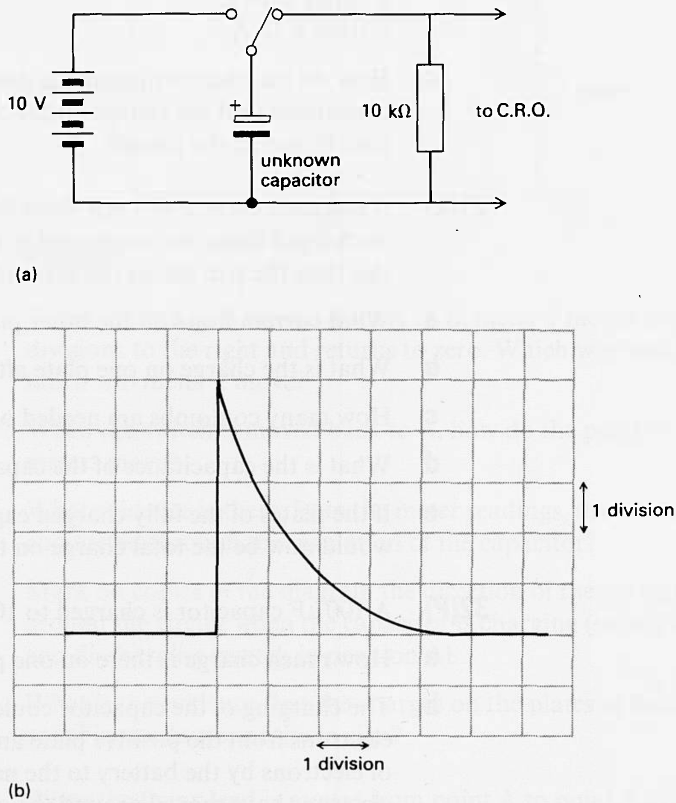


Figure B81

When the capacitor is charged up to 10 V and discharged through the 10 kΩ resistor, the resulting oscilloscope trace is as illustrated in figure B81(b).

The time-base is set at 0.1 s per division, and the voltage sensitivity at 2 volts per division.

a What is the maximum discharge current?

b Estimate the quantity of charge which flows around the circuit during discharge.

c Use the equation $C = Q/V$ to estimate the value of the unmarked capacitor.

d Using a similar scale to figure B81(b), sketch the traces which would be observed on the oscilloscope if the capacitor had:
i half the capacitance of the original;
ii twice the capacitance of the original.

34(L) *Capacitors in parallel*

This question explains how capacitors in parallel add up.

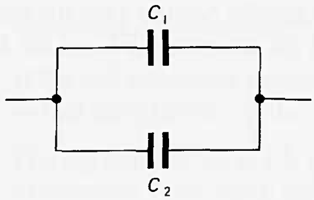


Figure B82

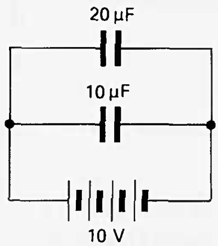


Figure B83

a What charge is stored on a 10 µF capacitor connected to a 10 V supply?

b What charge is stored on a 20 µF capacitor connected to a 10 V supply?

c In figure B83 what is the potential difference across the 20 µF capacitor when it is fully charged?

d What is the potential difference across the 10 µF capacitor when it is fully charged?

e What is the total charge stored in the arrangement in figure B83?

f What single capacitor would store the same charge as the two together?

g Is the following statement correct? 'Capacitances in parallel add up because their charges add up and the p.d. across each capacitor is the same.'

35(L) *Capacitors in series*

The following question explains how to calculate the total capacitance of the combination in figure B84.

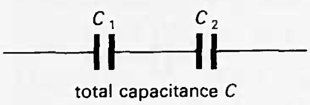


Figure B84

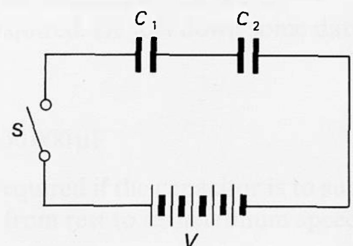


Figure B85

a When switch S is closed both capacitors start to charge.
i In a series circuit can the current flowing in one part of the circuit be larger than in another part?
ii Can the current flow in one part of the circuit for a longer time than in another part? (Think of Kirchhoff's Laws.)

b Can the capacitors have different charges on their plates? Explain your answer.

B

c If the charge that flows round the circuit is Q, what is the potential difference, V_1, across the capacitor C_1 in terms of C_1 and Q?

d What is the potential difference V_2 across capacitor C_2?

e By Kirchhoff's Second Law the sum of the potential differences around the circuit must equal the battery e.m.f.
Show that

$$V = \frac{Q}{C_1} + \frac{Q}{C_2}$$

and hence that

$$\frac{V}{Q} = \frac{1}{C_1} + \frac{1}{C_2}$$

f If V is the p.d. across the whole circuit and Q is the charge flowing around the circuit, what is the capacitance, C, of the whole circuit?

g You should now be able to show that

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

h Discuss the following:
Capacitors connected in series must have the same charge on their plates, and the p.d.s across both capacitors must add up to the supply voltage, therefore

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

The result that the total capacitance of two capacitors connected in series is less than either capacitance is often useful in constructing electronic circuits.

36(P) This question is about the circuit in figure B86.

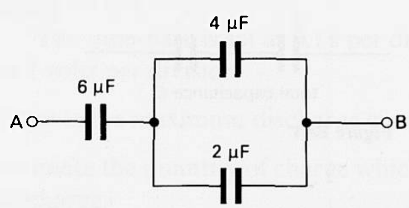


Figure B86

a What is the total capacitance between points A and B?

b It is found that as the p.d. across AB is increased, the insulating material between the plates of the 4 μF capacitor suffers electrical breakdown (it starts to conduct and its capacitance falls to zero). What is the equivalent capacitance now?

Energy in capacitors

37(L) Electric charge is stored on a capacitor, and as indicated in figure B87, at 20 V the charge stored is 0.2 C.

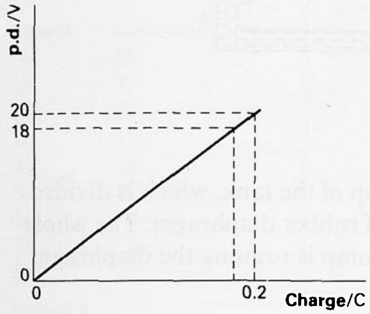


Figure B87

a What is the capacitance?

b If the p.d. across the capacitor dropped to 18 V, how much charge would have flowed off the capacitor?

c During this discharge the p.d. was first a little above 19 V, and then a little below. How much energy was transformed? Shade, on a copy of figure B87, an area that represents this energy.

d If the p.d. drops from 18 V to 16 V the same charge will flow. Will the energy transformed be the same? What will it be? (Take an average p.d. again.)

e On your copy of figure B87, shade in an area which represents the total energy transformed when the p.d. drops from 20 V to 16 V.

f By considering the energy transformed every time the p.d. drops by 2 V, calculate the total energy transformed when the capacitor discharges.

g The total energy can also be calculated using the formula $\frac{1}{2}QV$. Why are the two answers the same? What area on figure B87 represents this total energy?

38(P)a Calculate the energy that can be stored in a 10 000 μF capacitor capable of being charged to a p.d. of 30 V.

b This capacitor is then discharged through a photographic flash tube. If the power output of the flash tube is 500 W, for how long does the flash last?

39(E)a A student is designing an electric car. He has heard that capacitors store electrical energy and starts some calculations on the size of capacitance and charging voltage required. He jots down some data:

Mass of car 500 kg
Top speed 30 m s^{-1}
Largest capacitance available 100 000 μF

Calculate the charging voltage required if the capacitor is to supply enough energy to accelerate the car from rest to its maximum speed.

b Comment on your answer and the feasibility of using capacitors to store large amounts of electrical energy.

40(E) Figure B88 shows a plan view of a model intended to represent a capacitor in a circuit.

B

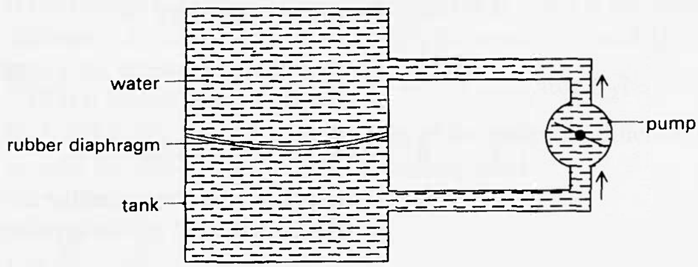


Figure B88

The pump pushes water into the top of the tank, which is divided into two compartments by a leakproof rubber diaphragm. The whole model is filled with water. When the pump is running the diaphragm bulges as shown.

a A student says that the device doesn't store water but that the capacitor does store electricity, so it is a poor model. Comment.

b Does the model store energy?

c How would you modify the model to represent an increase of capacitance?

d For a capacitor, charge is proportional to potential difference. What quantities would you measure to investigate whether an analogous relationship holds for this model?

e A small leak occurs in the rubber diaphragm. What would be the analogous situation for a capacitor?

Exponential changes

41(P) When a 100 μF capacitor is charged though R_1, as shown in figure B89(a), the graph of current against time looks like the one in figure B89(b).

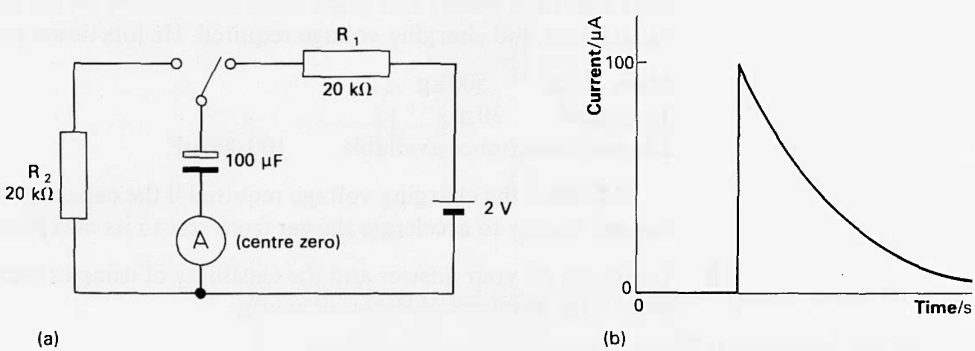


Figure B89

a Sketch the graph of current against time when the switch is now connected to R_2 (assume the resistance of the meter is small).

b Now sketch the graphs you would expect if the process were repeated with $R_1 = R_2 = 40\,\text{k}\Omega$. Remember that the area under the graph represents the total charge, which must be the same as before, but that the currents will be different.

42(P) A 400 μF capacitor is discharged through an unmarked resistor. Table B4 shows readings of current against time.

Time/s	Current/μA
0	50
10	39
20	30
30	23
40	18
50	14
60	8
70	6
80	5

Table B4

a Plot a graph of current against time and estimate the value of the resistance.

b To what p.d. was the capacitor originally charged?

c Estimate the quantity of charge on the capacitor using the area under the current–time graph. How does this compare with the value obtained by using $Q = CV$?

d Sketch the graph which would have been obtained if the capacitor had been initially charged to 15 V.

B

43(E) Table B5 shows the monthly figures for sales and rent of video recorders during 12 consecutive months.

	January	February	March	April	May	June	July	August	September	October	November	December
1000s of sets	1.5	1.64	1.8	1.96	2.19	2.36	2.57	2.8	3.06	3.33	3.8	4.3

Table B5

a Plot a graph of monthly sales and rentals against time.

b How many sets were rented or sold during the year?

c Find the ratios of sales in one month to the sales in the previous month. For example, June/May, $\frac{2.36}{2.19} = 1.08$.
What do you notice about these ratios?

d How do you account for the anomalies in November and December?

e Why do you think sales of video recorders have increased exponentially?

f Plot a graph of lg (monthly sales or rental) against time. Use the graph to predict how many months would pass before the monthly totals top the 100 000 mark. Is this prediction likely to be accurate, and if not, what other factors need to be taken into account?

44(E) A relay is a magnetic switch. Two contacts are closed when the coil creates a sufficiently strong magnetic field (figure B90). The smallest current through the coil which will close the contacts is 0.1 mA. The contacts can be used to switch a current of up to 4 A.

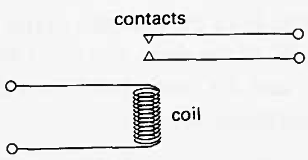


Figure B90

Invent a circuit based on a capacitor, variable resistance, and a relay for use as a photographic enlarger timer. For making exposures it is required to switch on the enlarger lamp for times ranging from 5 to 15 seconds. (Give appropriate values and state any assumptions you make.)

Electrons

45(P) The beam current in a cathode ray tube is 1 mA. How many electrons hit the screen in

a one second?

b one microsecond?

c 10^{-12} s?

d Could the tube be used to test the suggestion that the charge is in fact carried by particles with a finite charge?

46(P) How fast is an electron going if it has an energy of

a one electronvolt?

b 100 electronvolts?

47(E) Estimate the energy emitted from the screen of a television set. (Compare it with the brightness of a lamp of known power – preferably a fluorescent lamp.) If the electrons in the tube are accelerated by a p.d. of 20 kV, estimate the minimum current required to maintain the picture. How many electrons per second per square millimetre of the tube face does this give?

48(L) The results shown in table B6 were obtained with a Millikan apparatus, using oil drops. For each of several drops, the experimenter measured the potential difference across the plates (which were 4.42 mm apart) at which each charged drop was just held poised against the gravitational pull of the Earth. The weight of each drop was found by calculating it from the observed steady speed of fall in the air between the plates.

a Suppose an object with charge Q lies between the plates and the plates have a potential difference V across them. How much energy would be transformed if the charge Q moved from one plate to the other?

b Suppose the plates are a distance d apart, and a steady force F is exerted on the charge. How much energy would be transformed if an object were moved under force F from one plate to the other?

c If the pull, F, of the charged plates on the charge, Q, balances the weight, W, of the drop, the drop will be held at rest. Express Q in terms of W, V, and d. Check that C (coulomb) is the unit of measurement for your expression for Q.

d Find the charge on each drop in the results in table B6.

e Try to identify a basic charge e, such that each charge Q is some whole number multiple n of e ($Q = ne$).

f Given that other experimenters have shown that Q is always accurately a whole number multiple of $e = 1.6 \times 10^{-19}$ C, what do you think about the accuracy with which this experimenter was determining the balancing p.d.s and drop weights?

V **p.d. to balance drop/V**	W **Weight of drop/N**	Q **Charge on drop/C**	n **Multiple**
470	5.05×10^{-14}		
820	5.90×10^{-14}		
230	3.35×10^{-14}		
770	2.85×10^{-14}		
1030	3.65×10^{-14}		
395	7.00×10^{-14}		

Table B6

B

Unit C
DIGITAL ELECTRONIC SYSTEMS

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Emanuel School, London

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SUMMARY OF THE UNIT

'If the aircraft industry had evolved as spectacularly as the electronics industry over the past 25 years, a jumbo jet would cost £300 and it would circle the globe in 20 minutes on 20 litres of fuel.'

Adapted from: Hoo-min D. Toong and Amar Gupta 'Personal computers'.

C

SUMMARY OF THE UNIT

INTRODUCTION

Electronics provides a very powerful tool for the physicist and the engineer. Today, few physicists work without the aid of a micro-computer to control experiments and to read, store, process, and analyse data from experiments. Computers provide a means of developing and testing theoretical models, and to use them effectively requires some understanding of the basic processes that take place within them.

The circuits studied in this Unit are at the heart of the microprocessor (the integrated circuit which has made the microcomputer possible). Together with linear circuits (which you will learn more about in a later Unit), the microprocessor has made a big impact on our lives. It has made the industrial robot a reality; it is revolutionizing communications systems; in the home it controls the modern washing machine.

In the experiments in this Unit the logic gates that you will investigate are treated as black boxes. It does not matter whether you use circuits based on single transistors or integrated circuits. We will be concerned with how the output of a box depends on the input, not with what goes on *inside* the box.

You are asked to study the behaviour of each gate and then to make systems that will solve various problems. You will need some basic electric circuit theory, for example, the use of potential dividers and the action of capacitors in circuits.

When you attempt to solve the problems set in this Unit you are being asked to behave like an engineer. The task of engineers is to solve real problems, inventively using the resources available.

To begin with your resources may be rather limited, but they will grow as you design 'new' circuits.

When tackling a problem, engineers rarely start with equipment in front of them. The solution begins as an idea, perhaps inspired by knowledge and experience gained from earlier problems. These ideas may develop in discussion with other engineers, and will probably soon reach expression on paper. Only when a clear plan has been produced will engineers put their ideas into action. You are encouraged to follow that example.

Section C1 COMBINATIONAL LOGIC

Electronic systems

Everyone knows how to buy a hi-fi system. You either go for a 'music centre' which contains all the parts you need, or for 'separates'. Examining electrical circuits is a bit like that. You either look at the system as a whole or you look at bits of the system. Designing in electronics is a matter of putting parts together to produce a system which does the required job.

QUESTIONS 1 to 5

The parts of a music system are shown in figure C1.

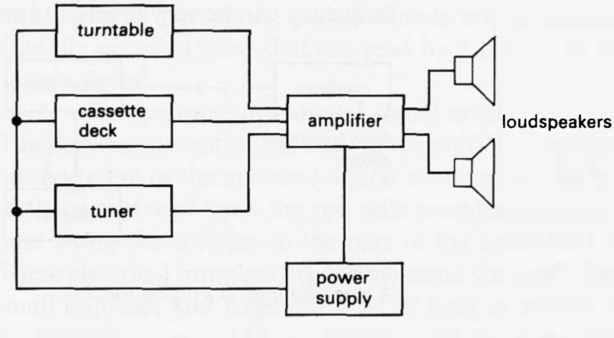


Figure C1
A music system.

When deciding on a hi-fi system it sometimes helps to consider each part individually. In the same way this can be helpful in designing electronic circuits.

A digital clock (figure C2) is a more complicated system. It uses the 50 Hz a.c. mains as a frequency standard. After being reduced to a suitable size (not shown in figure C2) the alternating voltage is changed from a sine wave to a square wave because square pulses are easier to count. Dividing by 50 gives us one pulse per second. The counter registers each pulse and the associated decoder and display circuits give a readout as a decimal number. The first counter counts from 0 to 9 and then starts again, having sent on a pulse to the next counter. The next counter counts up to 5, and then resets and passes on a pulse, and so on. Each counter passes its count at any instant to the display.

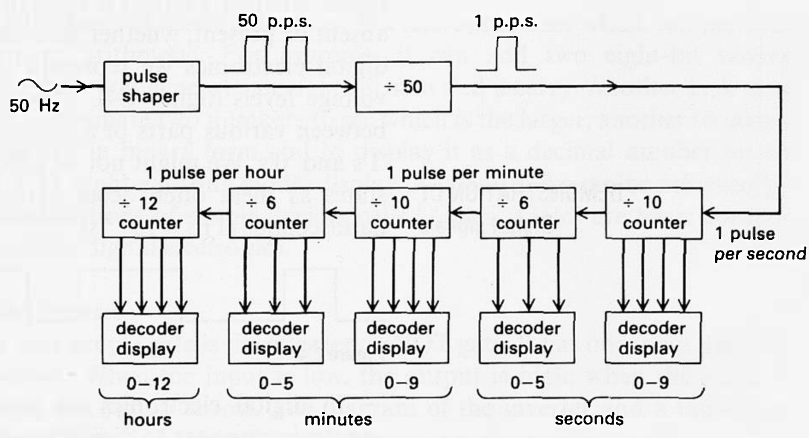


Figure C2
A digital clock.

This circuit could be made out of many separate transistors or a few integrated circuits. Nowadays it would be much more common to find all the components on a single integrated circuit (IC or 'chip'). All you need is a power supply, the 'clock' chip, a display, and a board to mount them on and you've got a clock.

To make a digital watch we need to use an internal oscillator to provide the reference frequency instead of the mains. The oscillator frequency can be very precisely controlled by a quartz crystal.

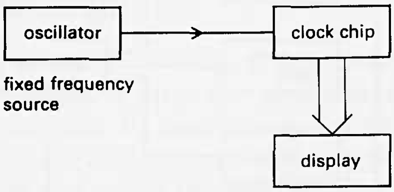


Figure C3
A block diagram of a digital watch.

Single integrated circuits that perform complicated tasks are very much the order of the day in modern electronics. Engineers look at what the circuit can do and can then fit it into a system. Few people, beyond the designer of the chip, know or care very much about how it works in any detail.

Digital systems

QUESTIONS 6 and 7

Binary arithmetic is the language of computers and of many electronic systems. Each 'bit' (BInary digiT) can either be 1 or 0, and can be stored as such in the computer's memory. 1 and 0 are the only states possible for a binary digital system. Groups of bits can represent data or instructions upon which the computer operates.

A wide variety of information can be represented by a 'two state' signal: whether a circuit is open or closed, on or off, whether a signal is absent or present, whether an event has occurred or not, and so on. In digital electronics we represent the digits 0 and 1 by low and high voltage levels (figure C4). If we examine the signals that are passed between various parts of a microcomputer, we would see a pattern of '1's and '0's. We might not be able to see the transitions between these states as these often occur extremely quickly, in times measured in nanoseconds (1 ns $= 10^{-9}$ s).

DEMONSTRATION C1
Digital signals

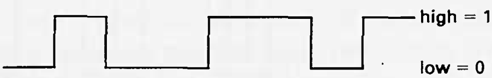


Figure C4

In digital electronics we generate digital outputs from circuits, usually in response to digital inputs.

Unit I, 'Linear electronics, feedback and control'

Much of the real world is not digital. Temperature variations are usually continuous, as are changes in light intensity and the alternating voltage output from a microphone. When dealing with such signals, you can either process them as continuously variable voltage signals, or convert them to digital signals and then process them in this form. One group of circuits that is of particular interest is those that convert linear signals to digital signals and vice versa. 'Analogue to digital converters' and 'digital to analogue converters' are found in many microcomputer systems.

READING
Digital sound (page 173)

Of the two systems we examined earlier, the hi-fi system is linear. However, digital methods are being used more and more as superior techniques of processing digital signals are developed – for instance, digitally encoded discs that are read by a laser. The digital clock is of course digital.

Another example of a digital signal involves no integrated circuits. The nervous system of the body is 'digital'. For example the 'rod' cells on the retina of the eye send digital messages to the brain. In response to the stimulus of light, the rod cells produce electrical impulses which pass along nerve fibres to the part of the brain that interprets vision. These electrical impulses are all the same size and shape. There are no small impulses and large impulses. If light of greater intensity falls on the rods they respond by producing pulses more rapidly, and vice versa.

The lower limit to the amount of light that the eye can see is the amount of light that stimulates one nerve impulse. Less light will not produce an impulse at all.

This picture is a little simplified; there is more than one rod in the eye. In fact one pulse from a single rod is not enough for the brain to 'see'. Some recent experiments have shown the brain 'sees' when about ten rods each send a pulse to the brain.

Our understanding of computer systems suggests new ways of thinking about the brain. It is not unusual to find that understanding of systems of one kind, electronic systems say, can be applied to systems in apparently unrelated fields.

C

Gates and truth tables

$$\begin{array}{r} 10110101 \\ +01100001 \\ \hline 1\ \underbrace{00010110}_{\text{sum}} \\ \text{carry} \end{array}$$

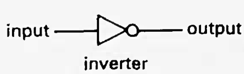
In the heart of a microcomputer is a microprocessor which can perform binary arithmetic. For example, it can add two eight-bit binary numbers and generate an eight-bit sum and a carry. Another task may be to compare two numbers to see which is the larger; another to take a number in binary form and to display it as a decimal number on an L.E.D. (light-emitting diode) display. All these tasks can be achieved by combinations of simple devices called 'gates'. Gates are basic components in digital electronics.

EXPERIMENT C2
The digital electronics kit

The inverter

EXPERIMENT C3
Investigating a single-input gate

A very simple gate is the inverter or NOT gate. It has one input and one output. When the input is low, the output is high; when the input is high, the output is low. The diagram of the inverter and a table that describes its behaviour (the truth table) are given in figure C5.



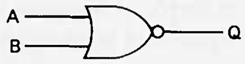
input	output
0	1
1	0

Figure C5

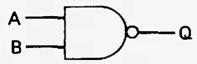
The NOR gate

EXPERIMENT C4
Investigating a NOR gate

The output of a two-input NOR gate is high when neither one input NOR the other input is high; that is, the output is only high when both inputs are low (figure C6).



NOR gate



NAND gate

inputs		output
A	B	Q
0	0	1
1	0	0
0	1	0
1	1	0

Figure C6

inputs		output
A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Figure C7

The NAND gate

EXPERIMENT C5
The behaviour of the NAND gate

A two-input NAND gate and its truth table are shown in figure C7.

NAND means 'NOT AND'; the output Q is NOT high when inputs A AND B are high.

QUESTIONS 8 to 12
and 31 and 32

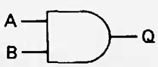
Both the NOR and the NAND gates are inverting gates – high outputs only occur with low inputs. It is convenient and very common practice to make inverters out of NOR or NAND gates. If the two inputs of each of these gates are joined together (figure C8) their truth tables become the same as that of the inverter.

Figure C8
Making an inverter from a NOR or a NAND gate.

Other gates

EXPERIMENT C6
Designing more gates

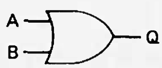
There are several other useful gates with two inputs. The symbols and truth tables of some are shown in figures C9 to C11.



AND gate

inputs		output
A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

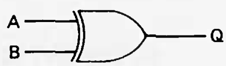
Figure C9



OR gate

inputs		output
A	B	Q
0	0	0
1	0	1
0	1	1
1	1	1

Figure C10



Exclusive OR gate

inputs		output
A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Figure C11

QUESTIONS 13 to 17

The non-inverting gate (figure C12) can be used to isolate one part of a system from another.

input	output
0	0
1	1

Figure C12

Hardware and software

Although it seems a large jump from these two-input logic gates to microprocessors, this jump is not as large as you may think. Among the many other functions that it can perform, a microprocessor can do the same job as simple logic gates.

A microprocessor has to be programmed: the program is a list of instructions and data. The instructions are written in code ('machine code'); the set of possible coded instructions for a particular type of microprocessor (such as the Z80 or the 6502) is called its 'instruction set'. Among the instructions that most have are those that instruct the processor to perform OR, Exclusive OR, and AND functions on two pieces of data, and NOT (or inverse) on one piece of data. The data may be in the program or it may be somewhere in the memory of the computer.

EXPERIMENT C7
Using a microcomputer to carry out logic functions

QUESTION 18

A programming language such as BASIC can be used to instruct a computer to carry out simple logic functions. These functions are part of the microprocessor's instruction set.

Logic gates: a more careful look at input and output voltages

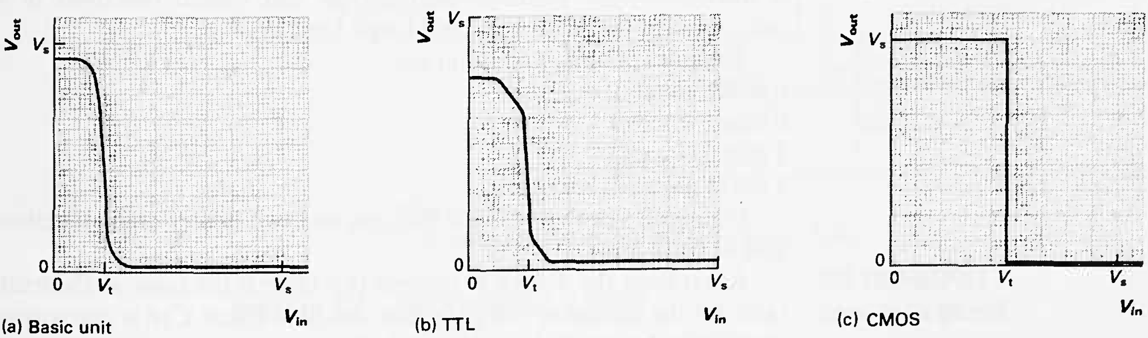
QUESTION 19

So far we have described voltages as being either 'high' or 'low'. Sometimes it is useful to know in more detail how the output voltage depends on the input voltage to the gate. This is easiest to investigate with an inverter, since it has only one input. These 'characteristics' depend on the type of gate used. Three types are likely to be encountered, based on:

i discrete components, for example, the 'basic unit'
ii TTL (Transistor Transistor Logic) integrated circuits
iii CMOS (Complementary Metal Oxide Semiconductor) integrated circuits.

EXPERIMENTS C8a and b
Measuring the characteristics of an inverter

Figure C13 shows approximately how each type of inverter behaves. V_s is the supply voltage.



(a) Basic unit (b) TTL (c) CMOS

Figure C13
Characteristics of inverters.

QUESTION 19

EXPERIMENT C9
Making a light-operated switch

QUESTIONS 20, 21, 22, 31, 34

The similarities between the graphs are more important than their differences. For all the inverters, an input lower than a certain value produces a high output and vice versa. There is a transition value of the input V_t, around which the output changes between high and low. This value is avoided in most logic circuits: the input voltage is fixed well below or well above V_t.

If we use one light-sensitive resistor and one fixed resistor in a potential divider that controls a gate, we can use a light level to control a logic circuit – we can make a light-dependent switch.

The system shown in figure C14 gives a high output when the light-dependent resistor (L.D.R.) is dark. The output could be made to go high in the light either by exchanging the positions of the L.D.R. and the other resistor, or by replacing the inverter with a non-inverting gate.

The gate can be controlled by some other physical parameter (for example, temperature) if the L.D.R. is replaced by some other sensor (for example, a thermistor – a resistor sensitive to temperature).

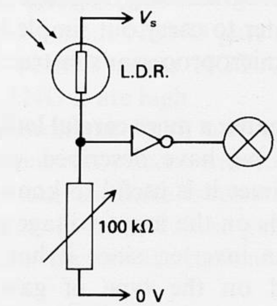
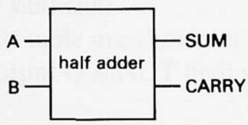


Figure C14
Light-dependent switch (for simplicity the 0 V connection to the indicating lamp is not shown).



inputs

A	B	SUM	CARRY
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

Figure C15
A half adder.

Binary addition

A microprocessor performs arithmetical and logical functions in a section called the Arithmetic and Logic Unit (ALU).

The rules of binary addition are:
0 plus 0 equals 0
0 plus 1 equals 1
1 plus 0 equals 1
1 plus 1 equals 0, carry 1.

Figure C15 shows a circuit that can add two binary digits together, and its truth table.

EXPERIMENT C10
Making a half adder

Apart from the 'CARRY' column this table is the same as the truth table for the Exclusive OR gate. The circuit in figure C16 is one way of producing this result. It is called a 'half adder'.

The half adder is all right for adding two digits together, but most calculations are more complicated!

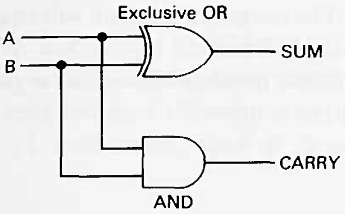


Figure C16
A half adder circuit.

Suppose we wish to add two numbers, A_1A_2 and B_1B_2 (for example 01 and 11).

$$\begin{array}{ll} A_2A_1 & A_1+B_1=S_1 \text{ with the CARRY } C_1 \\ B_2B_1 & A_2+B_2+C_1=S_2 \text{ with the CARRY } C_2 \\ \hline C_2S_2S_1 & \\ \hline \end{array}$$

$$\begin{array}{ll} & \leftarrow 1+1=0, \text{ CARRY } 1 \\ \;\;0\;1 & \\ \;\;1\;1 & \\ & \leftarrow 0+1+1=0, \text{ CARRY } 1 \\ \hline 1\;0\;0 & \\ \hline \end{array}$$

QUESTIONS 23 and 24

EXPERIMENT C11
Making a full adder

One half adder can add A_1 and B_1; but then we have to consider the CARRY from the first addition, C_1, as well as adding A_2 and B_2. A circuit which overcomes this problem is called a 'full adder' and is shown in figure C17.

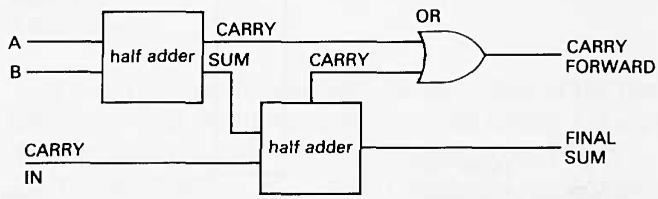


Figure C17
A full adder.

EXPERIMENT C12
Using a microcomputer to perform binary addition
Physics Reader
Microcomputer circuits and processes

In order to carry out the addition $A_2A_1+B_2B_1$ we would need the circuit shown in figure C18.

All that is needed to add two binary numbers with more bits is an extra full adder for each extra bit. The addition is always started from the right (the least significant digit) as in ordinary arithmetic.

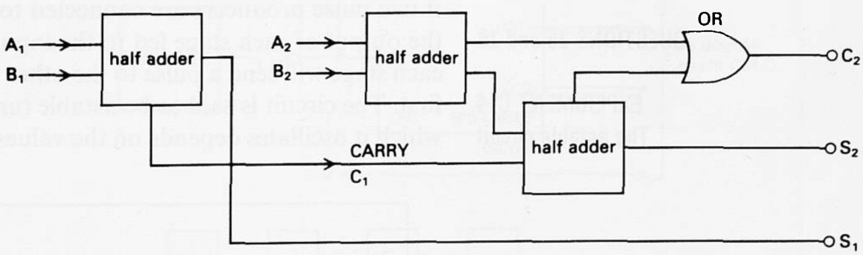


Figure C18
A circuit to add two two-bit numbers ($A_2A_1+B_2B_1$).

Section C2 SEQUENTIAL LOGIC

Making pulses

EXPERIMENT C13
Making pulses

If the switch in the circuit shown in figure C19 is moved from 0 V to V_s the input to the gate is made high and then falls exponentially at a rate determined by the values of C and R. The output of the gate will change state when the input passes from low to high or from high to low. When an inverter is used as in the diagram, the pulse produced is 'negative going' – figure C20(a) – that is, the output is normally high but goes low for the period during which the input is high (more than V_t, the transition voltage).

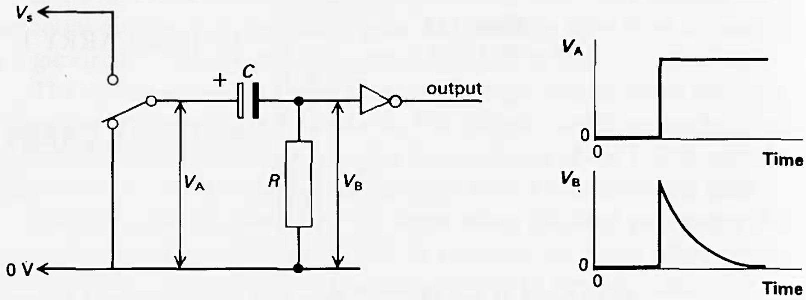


Figure C19

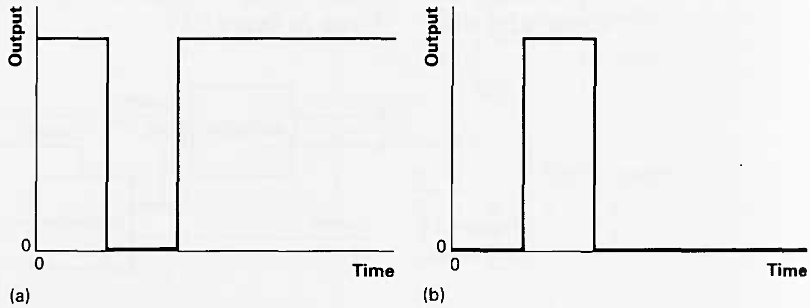


Figure C20
(a) Negative going pulse.
(b) Positive going pulse.

A positive going pulse – figure C20(b) – may be made by replacing the inverter with a non-inverting gate.

The astable circuit

QUESTIONS 25 and 26

EXPERIMENT C14
The astable circuit

If two pulse producers are connected together, one after the other with the output of each stage fed to the input of the other (figure C21), then each stage will send a pulse to the other stage which sends it back to the first. The circuit is said to be astable (unstable), and the frequency with which it oscillates depends on the values of the resistors and capacitors.

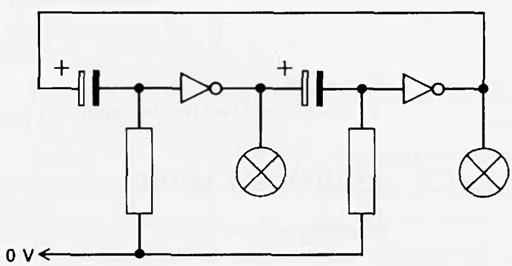


Figure C21
An astable circuit.

In practice, other astable circuits are normally used but they have their frequency controlled by an *RC* circuit in a similar way. An astable circuit may be used for many forms of timing if the pulses from it are counted, or for generating audible signals.

EXPERIMENT C15
Investigating the astable module

The bistable circuit

QUESTIONS 27 and 28

EXPERIMENT C16
The bistable circuit

This circuit, as its name implies, has two stable states. It is made by connecting a pair of inverters together as shown in figure C22. If the input to the first is high, its output and therefore the input to the second will be low. Hence the output of that will be high, keeping the input to the first high. The circuit is also stable with the input to the first low.

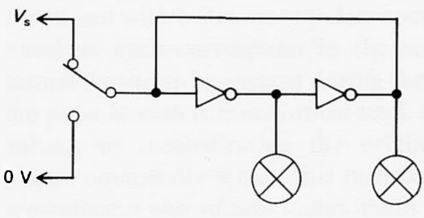


Figure C22
A bistable circuit.

EXPERIMENT C17
The bistable module

QUESTIONS 29 to 31

This circuit can be used as a memory. One of the states represents the binary digit 0, the other representing binary 1. Large numbers of bistable circuits are used in the memories of computers.

A clocked bistable module, as provided in the electronics kit, can be used to divide by 2. Each pulse going into the module changes it from one state to the other. So *two* pulses are needed to get the bistable module from one state to the other and back to the first, that is, to get one pulse out.

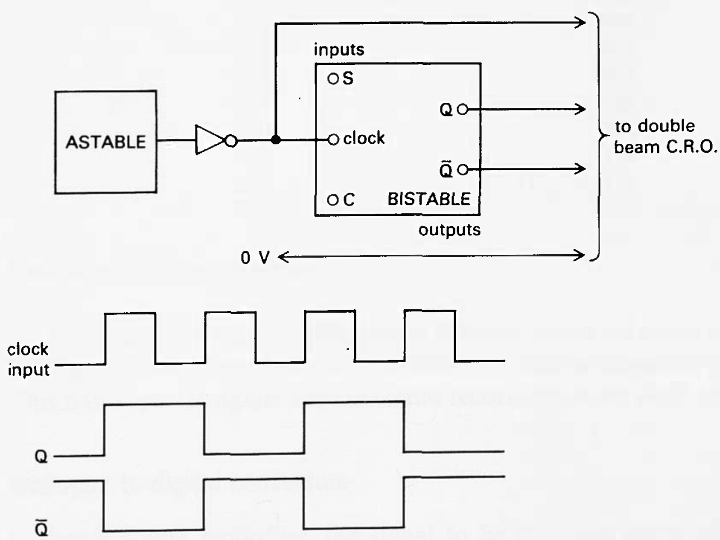


Figure C23
Investigating the bistable module.

Section C3 DESIGNING DIGITAL SYSTEMS

EXPERIMENT C18
Designing digital systems

The basic devices and principles of digital electronics are the basis of many modern communication and control systems, from turning on a lamp through the programming of a domestic washing machine to the automatic control of complex manufacturing processes. Most computers and *industrial robots* use the same digital ideas.

You can start exploring some of these possibilities with the digital electronics kit.

READING

DIGITAL SOUND

(Adapted from J. Borwick *The Gramophone guide to hi-fi*, David & Charles, 1982.)

Introduction

The future of every aspect of sound recording and reproduction is dependent on digital techniques.

Put simply, digitalization consists of replacing the audio signal waveform with a stream of pulses encoded to represent numbers. These numbers each correspond to the amplitude of the signal waveform sampled instant-by-instant during the recording process. For playback, the pulse stream is transformed back to instantaneous signal amplitude values, so reconstituting the original waveform. The considerable circuit complexity which this technique requires at the recording and reproducing end of any audio chain has become a practicable reality only because of the accelerating development of integrated circuits and microprocessors.

C

Binary numbers

At the heart of these developments is the use of a binary scale of numbers. Table C1 shows how the binary scale works in the particular case of a 'word' of four binary digits ('bits').

Decimal	Powers of 2	Binary	Decimal	Powers of 2	Binary
0		0000	8	2^3	1000
1		0001	9		1001
2	2^1	0010	10		1010
3		0011	11		1011
4	2^2	0100	12		1100
5		0101	13		1101
6		0110	14		1110
7		0111	15	(2^4-1)	1111

Table C1
Decimal and binary scales compared.

Our four-bit word can have sixteen different values (of which one is 0). In general a word-length of n bits provides 2^n values as shown on table C2. This has a special significance in sound recording, as we shall see.

Analogue-to-digital conversion

In digital sound recording, the signal to be recorded starts off as an electrical imitation or 'analogue' of the original sound waveform (see

Number of bits, n	Range of values, 2^n	Signal-to-noise ratio/dB*
1	2	6
2	4	12
3	8	18
4	16	24
5	32	30
6	64	36
7	128	42
8	256	48
9	512	54
10	1 024	60
11	2 048	66
12	4 096	72
13	8 192	78
14	16 384	84
15	32 768	90
16	65 536	96

Table C2
Range of values provided by different word lengths.

figure C24). To convert this to digital form, the amplitude of the waveform is sampled at regular intervals of time and each sample is encoded and stored as a binary number corresponding to its value on a fixed amplitude scale. In the four-bit words used, only sixteen different binary code numbers are possible (as we have seen from table C2).

The digitally encoded signal is made up of pulses for the symbol 1 and blank spaces for 0, the system being referred to as pulse code modulation (p.c.m.). The process of allocating each sample a binary code number is called quantizing, and clearly involves some approximation since the analogue waveform will usually be at some intermediary

**Note on the decibel scale*

The decibel scale is a method of expressing the ratio of two powers.

If voltages are known one calculates $20\log_{10}(V_1/V_2)$.

For example, the ratio between 12 V and 6 V is

$$\frac{12\text{ V}}{6\text{ V}} = 2$$

In decibels

$$20\log_{10}\left(\frac{12\text{ V}}{6\text{ V}}\right) = 20\log_{10}2\text{ dB}$$
$$= 20 \times 0.30\text{ dB}$$
$$= 6\text{ dB}$$

The signal-to-noise ratio of a digital signal is the ratio between the number of bits that represent a signal level and the maximum error (noise) that could be present (1 bit).

So for a 16-bit system, the signal-to-noise ratio is

$$\frac{2^{16}}{1}$$

or

$$20\log_{10}\frac{2^{16}}{1}\text{ dB}$$

$$= 96\text{ dB}$$

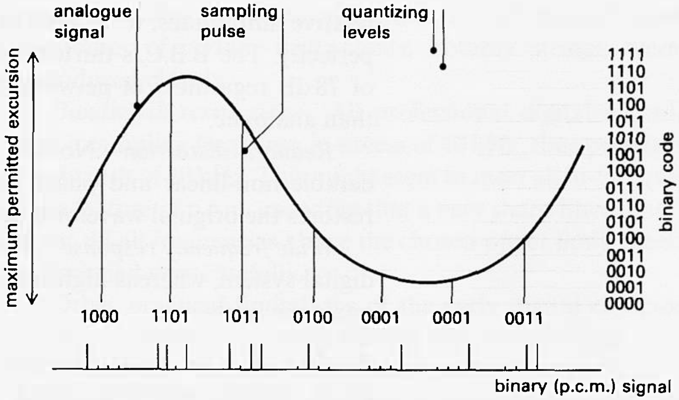


Figure C24
In digital recording, the analogue waveform is sampled at fixed time intervals and each sampled level is expressed or 'quantized' in binary code.

amplitude when sampled. This approximation leads to 'quantization noise' but this can be reduced to very acceptable proportions by using more bits. This is confirmed by the last column of table C2 which lists the signal-to-noise ratio obtainable for p.c.m. systems using up to sixteen bits.

Provided the sampling frequency is more than twice the highest sound frequency to be recorded, it has been found that the waveform can be recorded and reproduced to high standards of accuracy. If an audio bandwidth of 15 kHz is considered adequate, for example, a sampling frequency of 32 kHz might be chosen. Where fidelity up to 20 kHz is required, the sampling frequency might be 44 kHz or 50 kHz. To record or transmit p.c.m. digital signals, the system requires a bandwidth at least equal to the sampling frequency multiplied by the word-length in bits. Thus a sixteen-bit system with a sampling frequency of 50 kHz would need a bandwidth of 800 000 Hz per channel – well beyond the capabilities of ordinary sound recording equipment.

Digital evolution

One of the first important applications of digital audio techniques was the B.B.C.'s construction of a p.c.m. network for distributing radio programmes to its various transmitting stations in the late 1960s. Though this was only a thirteen-bit system with a 32 kHz sampling frequency (audio bandwidth is in any case restricted to 15 kHz on VHF/FM radio) it produced a dramatic improvement in broadcast quality. The important advantages of digital sound which appeared in this application included the following:

Reduced noise Whereas noise is a continual nuisance in analogue distribution networks, becoming worse with each mile of landline or radio link travelled, it can effectively be ignored in the digital system. The digital-to-analogue converter at the receiving end of the line has only to recognize the presence or absence of pulses, not gauge their relative amplitudes, to be able to reconstitute the sound signal almost perfectly. The B.B.C.'s thirteen-bit system gives a signal-to-noise ratio of 78 dB regardless of network distance (see table C2) – much better than analogue.

Reduced distortion Normal analogue networks introduce considerable non-linear and phase distortion, whereas the digital process restores the original waveform practically undistorted.

Wide frequency response The full 15 kHz range is preserved in the digital system, whereas high-frequency losses were almost inevitable in analogue lines.

Around 1972, the Nippon Columbia Company of Japan (Denon) began p.c.m. sound recording, using professional videotape recorders to provide the necessary bandwidth. The conventional analogue LP records which they produced from these digital master recordings showed a degree of clarity compared with discs manufactured from analogue tape masters. In addition to the three advantages of the digital process mentioned above, the new master tapes possessed the following:

No wow-and-flutter Because the replay system relied on an accurate quartz clock to synchronize the sampling rate on replay with that recorded, the usual short-term pitch fluctuations normally associated with tape (and disc) systems were eliminated.

No tape modulation noise Analogue tape introduces several types of noise such as granular hiss, modulation noise, and print-through. These are all avoided in digital recording.

Improved channel separation As the left and right stereo signals are encoded separately, very little interchannel crosstalk takes place.

With such a formidable array of advantages, it is not surprising that most of the major record companies and independent studios soon followed the Nippon Columbia lead and installed digital machines for master recording. The designs varied, some using videotape equipment and others data storage units. This made it difficult to exchange recordings between studios, since each digital master could only be played back on the same type of machine on which it had been recorded. However, the in-house benefits were considerable. Masters did not deteriorate in store and copies could be virtually identical to the original.

By 1980, many of the LP records coming on to the market bore the word 'Digital', and the companies stressed the advantages of the new recording technique in their advertisements and sleeve-notes. It was, however, perfectly obvious – and often reiterated by the critics – that the different digital mastering machines gave inconsistent sound quality: that indeed these early digital recorders had limitations as well as advantages. These limitations included:

Increased distortion at low levels While distortion in analogue recording increases at high signal levels, the opposite occurs in digital. Resolution deteriorates at low quantizing levels leading to quite severe distortion. Techniques exist for disguising this effect, so that it is barely audible under most conditions. Nevertheless, degrees of acoustic dryness and tonal hardness were noticed in many early digital recordings, suggesting that the reverberant 'tail' of musical sounds, and the harmonics of certain instruments, notably strings, were not being reproduced cleanly.

Bandwidth restrictions All professional digital recording systems used a sampling frequency in excess of 40 kHz, thus permitting an audio bandwidth of 20 kHz. This might seem to meet all hi-fi requirements but it is a feature of p.c.m. encoding that a very sharp filter must be included to cut off all frequencies above the chosen upper limit. Such filters must be designed very carefully.

Other practical limitations of the early digital equipment affected the way in which it was used. Editing was more difficult, for example, so that musicians were encouraged to make longer 'takes' with fewer stoppages. Ironically, this gave rise to some favourable comment from critics, who felt that editing had previously become too prevalent in the recording studios. Again, digital masters were mainly two-track only, so that balance engineers often felt obliged to go back to a simpler microphone technique and mix-down straight to two-track stereo. This was in contrast to the multi-microphone multi-track procedures evolved over recent years, yet, as with the simpler editing, it frequently produced a more natural, cleaner sound balance which drew critical acclaim for many of the new 'digital' LP records, even though it was an indirect, rather than a direct, consequence of the adoption of a digital mastering process.

Digital discs

While the so-called 'digital' LP records could, in the best examples, be identified as possessing at least some of the benefits inherent in the original studio master recordings, they were nevertheless cut and pressed in analogue form and by the old traditional methods. They were therefore subject to all the same limitations and just as easily damaged or invaded by dust and static as conventional LPs.

It was obvious that, if all the benefits of digital recording were to be enjoyed in the home, the sounds must be retained in digital form right up to the moment of playback. Research into truly digital disc systems was intensified and soon about half a dozen competing types were being demonstrated at engineering conventions and trade shows. This diversity of incompatible domestic systems, with each disc unplayable except on its own machine type, was much more serious in commercial terms than the similar lack of standardization amongst professional studio equipment. The general public would like to be able to buy records in the shops without having to select a particular format suited to their own player unit. A great deal of confusion already exists in the videotape market, for example, where three quite different incompatible tape cassette formats are in general use at the time of writing – VHS, Beta, and V2000.

C

The Compact Disc

Pride of place must be given to the laser-scanned Compact Disc developed by Philips in Holland, with subsequent collaboration from Sony in Japan. This is the most technically advanced of the systems so far on offer and has a number of important practical, as well as high-quality, features.

As with the earlier Philips invention, the Compact Cassette, the small size of the Compact Disc is already an attractive feature. The disc is only 120 mm (4.7 inches) in diameter and consists of clear PVC 1.1 mm thick. The digital sound signals are pressed into the PVC, on one side only, in the form of tiny pits or indentations measuring a mere 0.6 μm across. The binary code is represented by pits for the 1 symbols and blank spaces for 0. The track spirals outwards from the disc centre and the microscopically small track spacing of 1.66 μm gives up to 60 minutes of stereo music per disc. During manufacture, the stamped out PVC surface is given a thin coating of reflective aluminium and this in turn is overlaid with a transparent 0.15 μm coating. A fixed linear track speed of about 125 cm s^{-1} is employed and so the rotational speed decreases as the record plays, being about 500 r.p.m. at the centre and 215 r.p.m. at the outer edge.

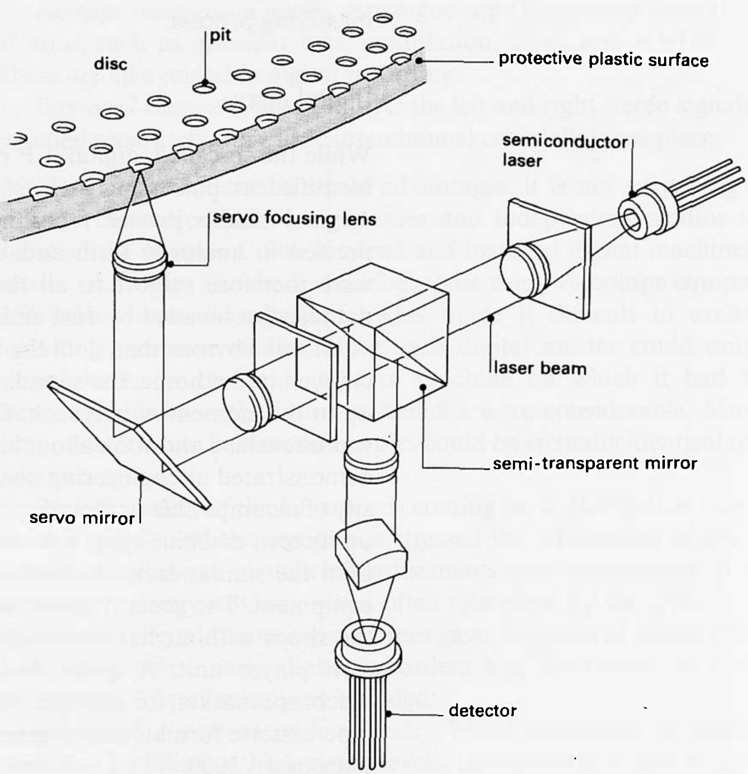


Figure C25
Playback system for the Compact Disc, showing the semiconductor laser light source, the system of lenses and mirrors, and the detector which receives the pulses reflected from the disc surface.

As shown diagrammatically in figure C25, the optical playback system consists of a laser light-source, a series of lenses and mirrors, and a light-sensitive detector. The laser beam is reflected and focused so as to scan the helical track of pits and blank spaces from underneath the disc. As pits and blank spaces are scanned, the laser beam is either scattered or strongly reflected back downwards to be picked up by the photo-electric detector and converted into pulses of electric current. Thus the original digital signals have been reproduced and can be changed back into analogue form by a digital-to-analogue converter built into the player. The stereo electrical output of a Compact Disc player is therefore similar to that from a conventional record-player, tuner, or cassette deck and can be connected to any hi-fi amplifier or domestic system.

Though the mass-production techniques for the Compact Disc are basically similar to those used for vinyl LPs, the small dimensions and close tolerances needed demand extremely high standards of air cleanliness and quality control measures. For the user, however, the Compact Disc is an extremely robust medium. Dust or finger marks are ignored by the laser beam and the normal problems of stylus cleaning and careful pick-up alignment are a thing of the past. Also, since there is no physical contact, there is no wear of the recorded track or the scanning mechanism. The player itself can be quite small, yet the *constant linear speed* feature allows more flexible access and cueing facilities than the conventional LP. In technical terms, the Compact Disc uses a sixteen-bit format with a sampling frequency of 44.1 kHz. This gives a claimed frequency response up to 20 kHz, immeasurable wow-and-flutter, with dynamic range and channel separation of up to 90 dB.

While the Philips Compact Disc uses the same basic principle of a pitted surface and laser-beam scanning as their 300 mm diameter Laser Vision video disc system, the two media are in all other ways incompatible. Philips and their associated companies are convinced that separate players and different standards are preferable for digital audio and television playback.

Questions

a A flute plays the note A (frequency, $f = 440$ Hz) into a microphone. The output signal of the microphone amplifier, V, varies with time according to $V = V_0 \sin 2\pi ft$. V_0, the maximum value of the output is 1.5 V.

i What is the value of the signal at the following times: 0, 0.1 ms, 0.2 ms, 0.3 ms, 0.4 ms, 0.5 ms, 0.6 ms?

ii Using the four-bit binary number 1000 to represent 0.8 V, express each of the answers to *i* in similar form.

iii In parts *i* and *ii* you have been digitalizing an analogue signal using four bits and a sampling frequency of 10 kHz. Explain, with reference to your results, why more bits and higher sampling frequencies are used in practical systems.

C

b A microphone amplifier needs an input of 0.5 mV for an output of 1.5 V.
What is its gain
i expressed as a ratio
ii expressed in dB?
Power levels are compared on the dB scale using the formula

$$10\log_{10}\left(\frac{P_1}{P_2}\right)$$

Current and voltage levels use the formulae

$$20\log_{10}\left(\frac{I_1}{I_2}\right) \text{ and } 20\log_{10}\left(\frac{V_1}{V_2}\right)$$

Explain why the figure 10 occurs in the power formula and 20 in voltage and current ones.

c *i* Explain the term 'hi-fi' (high fidelity).
ii Why is digital transmission more faithful than the transmission of an analogue signal?

d *i* Using the figures given in the passage, calculate the maximum length of the recording track on a Compact Disc.
ii Estimate the separation between adjacent tracks on the disc and check that it is consistent with the quoted figure of 1.66 μm.

LABORATORY NOTES

DEMONSTRATION
C1 Digital signals

C1a Simple circuit having two states

mounted bell push
lamp, *e.g.*, 2.5 V m.e.s.
holder
cell holder with two cells
leads

N.B. The lamp must, of course, have a second connection to the power supply, but to simplify the drawing we omit it here and elsewhere. But don't forget it is always included.

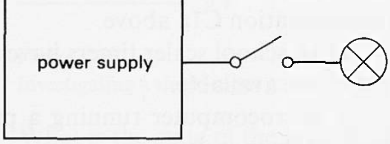


Figure C26

How many possible states does this circuit have?
What are these states?

C1b Slow electronic flashing circuit

digital electronics kit with power supply
leads

In what way is this circuit similar to figure C26?

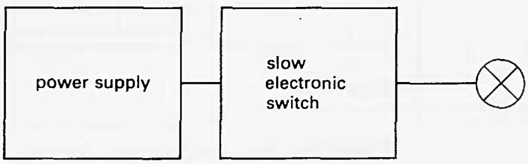


Figure C27

C1c Fast electronic flashing circuit

digital electronics kit with power supply
oscilloscope
leads

How many states does this circuit (figure C28) have?
How can you tell?

C

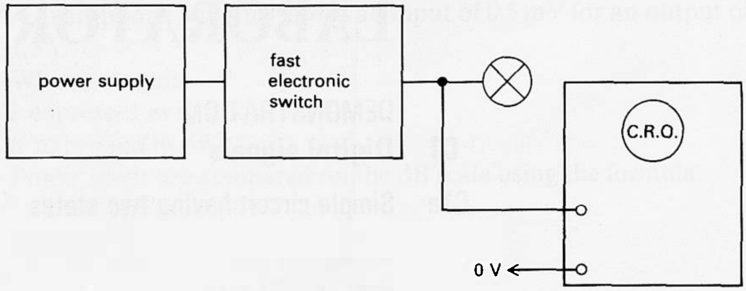


Figure C28

C1d Other sources of digital signals

Many familiar pieces of equipment depend on digital signals. For example, when a single digit, say 6, is dialled on a mechanical telephone dial, a mechanical switch opens and closes six times. A signal consisting of 6 pulses is sent. It could be used to control a lamp as in demonstration C1a above.

Most school scaler timers have sockets at which their internal clock pulses are available.

A microcomputer running a program has digital signals at many parts of the circuit.

EXPERIMENT

C2 Introducing the digital electronics kit

digital electronics kit with power supply
voltmeter appropriate to the power supply
leads

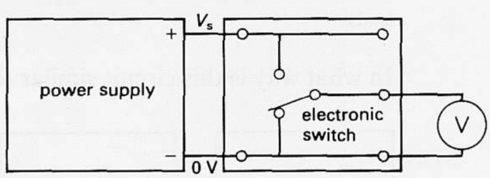


Figure C29

Examine the electronics kit or the manufacturer's instructions to determine the voltage of the power supply required (V_s). Then connect the circuit as shown in figure C29.

The circuit gives two outputs, one that is low (near 0 V) representing the binary digit 0, the other being high (near V_s) representing binary digit 1. Use the voltmeter to get a more accurate value for the 'high' and 'low' voltages.

If your electronics kit has a separate indicator unit, connect this in place of the voltmeter. What happens? What advantage does this have over a voltmeter?

EXPERIMENT
C3 Investigating a single-input gate

digital electronics kit with power supply
leads

Take a NOR gate (which will probably be labelled with the symbol shown in figure C30) and connect an appropriate power supply. Identify the inputs to one gate (usually on the left), and the output. Connect the inputs together as shown to make a system with one input and one output. If your kit has separate indicators, connect one to show the state of the output.

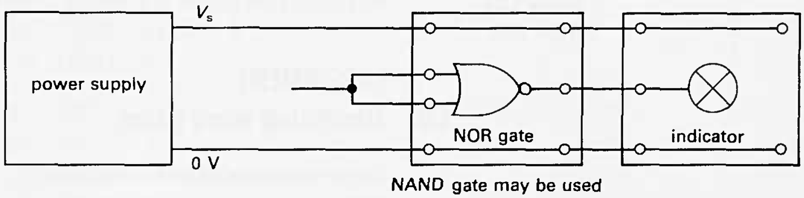


Figure C30
Investigating a single-input gate.

What is the state of the output when the input is low?
What is the state of the output when the input is high?
What happens when the input is unconnected?
Draw a table to record your results.
Suggest an appropriate name for this circuit.

EXPERIMENT
C4 Investigating a NOR gate

digital electronics kit with power supply
leads

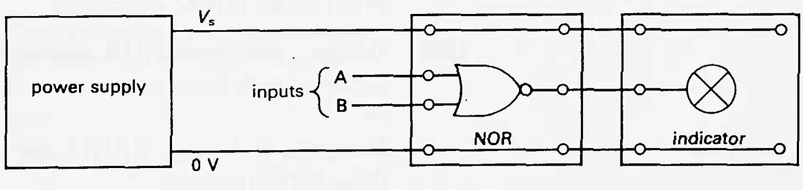


Figure C31
Investigating a NOR gate.

Using the two inputs to your gate, make a 'truth table' that describes the behaviour of the gate. Start by making both inputs low – is the output high or low? Make one of the inputs high. What state is the output now? Continue until you have tried all four combinations of inputs.
What could these gates be used for?
What happens if an input to the gate is not wired directly high or low but left 'floating'?
Why are they called 'gates'?

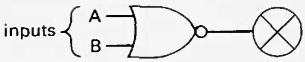


Figure C32
Simplified version of figure C31.

From now on we shall use the simplified form of circuit diagram shown in figure C32 for all circuits. The power supply lines V_s and 0 V must be connected up, but in general they will not be included in the diagrams. The symbol used for the NOR gate is a standard one. There is a summary of standard symbols on page 498.

EXPERIMENT
C5 The behaviour of the NAND gate

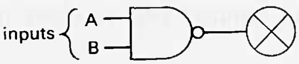


Figure C33
NAND gate.

digital electronics kit with power supply leads

Repeat experiment C4 with a NAND gate to establish its truth table.

EXPERIMENT
C6 Designing more gates

digital electronics kit with power supply leads

Try to work out solutions to these problems before you attempt to make the circuits. Remember that you can use NAND or NOR gates as inverters.

Suggest a use for each gate that you design.

C6a Design a two-input AND gate whose output is high when one input AND the other are high. This is very easy with NAND gates but harder with NOR gates. Try to solve the problem using both types of gate.

C6b Design a two-input OR gate whose output is high when one input OR the other OR both are high. This time it's easy with NOR and harder with NAND. Again, try both methods.

C6c Design a non-inverting gate whose output is the same as the input. What might this be useful for?

C6d Design a two-input NOR gate using NAND gates. The solution can be achieved with four gates.
or:
Design a two-input NAND gate using NOR gates. Again, it can be done with four gates.

C6e Design a three-input NOR gate using two-input NOR gates. This task can be done with three gates.
or:
Design a three-input NAND gate using two-input NAND gates. Again this can be done with three gates.

C6f Design a two-input Exclusive OR gate: a gate whose output is high when one input OR the other is high but not when both are. The best solution to this uses two NOR gates and a single AND gate.

EXPERIMENT

C7 Using a microcomputer to carry out logic functions

microcomputer with BASIC language

The following programs demonstrate how the logic functions NOT, OR, and AND work on a microcomputer.

```
10 INPUT A
20 PRINT NOT A
30 GOTO 10
```

```
10 INPUT A
20 INPUT B
30 PRINT A OR B
40 GOTO 10
```

```
10 INPUT A
20 INPUT B
30 PRINT A AND B
40 GOTO 10
```

Try the programs and see what happens. For some microcomputers (for example, Sinclair, Apple), the inputs should be either 0 or 1. For other microcomputers (for example, Research Machines, B.B.C.), the inputs should be 0 or −1.

How can you use the functions NOT, OR, and AND to write a program that will perform **a** the NOR function, **b** the NAND function? Test your solutions.

Suggest a reason why the functions NOR and NAND are not standard in BASIC.

EXPERIMENT

C8a Measuring the characteristics of an inverter

digital electronics kit with power supply
2 voltmeters appropriate to the supply
potentiometer, 1 kΩ
leads

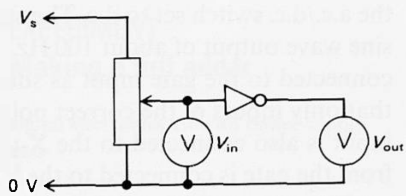


Figure C34
Circuit to measure the characteristics of an inverter.

Set up the circuit in figure C34. Remember that an inverter may be made from a NAND gate or a NOR gate with both inputs connected together as shown in figure C35.

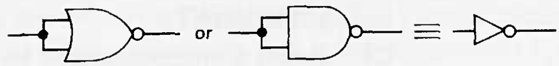


Figure C35
Making an inverter from NOR or NAND gates.

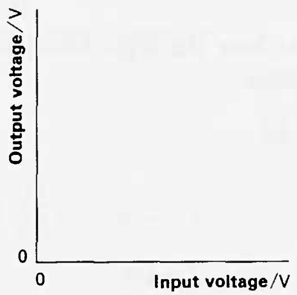


Figure C36

Use the potentiometer to vary the input voltage. For each value of input voltage, measure and record the output voltage. You may wish to change the input voltage in small steps when the output voltage changes. Draw a graph of output voltage against input voltage.

From your graph:

i When the input voltage is high, is the output voltage high or low?

ii Is there a distinct input voltage at which the output suddenly changes? If so, record that voltage.

ii Does the output change from high to low over a small range of input voltages? If so, what is the smallest change in input voltage that causes the output to go from high to low?

DEMONSTRATION

C8b Plotting the characteristics of an inverter on an oscilloscope

digital electronics kit with power supply
signal generator
oscilloscope
diode, *e.g.*, 1N4001
leads

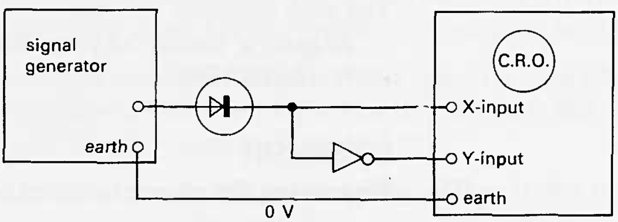


Figure C37
Using an oscilloscope to display characteristics.

The oscilloscope time-base is turned off and the oscilloscope used with the a.c./d.c. switch set to d.c. The signal generator should be set to give a sine wave output of about 100 Hz. The output of the signal generator is connected to the gate input as shown in figure C37. The diode ensures that only inputs of the correct polarity are applied to the inverter. This input is also connected to the X-plates of the oscilloscope. The output from the gate is connected to the Y-plates.

The output of the signal generator is increased to about 3 or 4 V until the voltage characteristic is plotted on the screen. It may be necessary to adjust the gain of the X- and Y-amplifiers and the position of the trace on the screen.

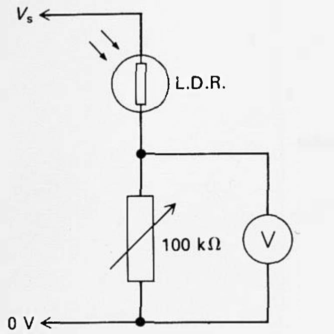


Figure C38
Potential divider with light-dependent resistor.

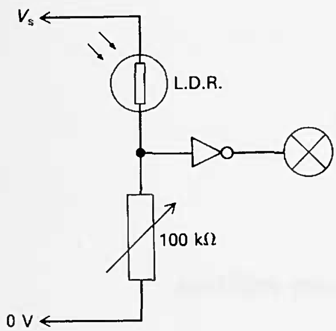


Figure C39
A circuit which turns a lamp on in the dark.

EXPERIMENT
C9 Making a light-operated switch

digital electronics kit with power supply
light-dependent resistor (L.D.R.) *e.g.*, ORP 12
resistance substitution box
voltmeter appropriate to the supply
leads

From experiment C8, determine the potential required at the input of an inverter to change the state of the output. Set up the circuit in figure C38 and investigate briefly how its output varies as the light incident on the L.D.R. varies.

What would you expect to happen if you connected this circuit to the input of the logic gate as shown in figure C39? When you have decided what you expect to happen, try it out.

Some discrepancy between the predicted and observed behaviour may occur. Explain.

The circuit you have made should make the indicator light when the illumination of the L.D.R. falls below a certain level. How would you change this circuit so that the opposite occurs, that is the indicator goes out when the light level falls?

C

EXPERIMENT
C10 Making a half adder

digital electronics kit with power supply
leads

Make a system to add the two digits A and B together to give a SUM and CARRY digit in binary arithmetic. This is called a 'half adder'.

A + B = SUM and CARRY

0 + 0 = 0	and 0
0 + 1 = 1	and 0
1 + 0 = 1	and 0
1 + 1 = 0	and 1

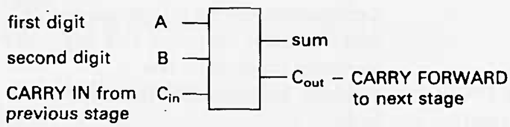
EXPERIMENT
C11 Making a full adder

digital electronics kit with power supply
leads

In experiment C10 you constructed a half adder which will add together two digits. A computer adding two numbers, like 1001110 and 1101101, will add them in pairs of digits starting at the right as usual. Except for the addition of the first pair of digits, any of the subsequent additions may also have to include a CARRY digit from the previous addition.

The block diagram (figure C40) describes what we wish to achieve together with the truth table.

Devise one stage of such a binary number adder, using two half adders and a small extra item.



inputs			outputs	
A	B	C_{in}	sum	C_{out}
0	0	0	0	0
0	0	1	1	0
1	0	0	1	0
1	0	1	0	1
0	1	0	1	0
0	1	1	0	1
1	1	0	0	1
1	1	1	1	1

Figure C40
Block diagram and truth table of a full adder.

EXPERIMENT C12 Using a microcomputer to perform binary addition

microcomputer with BASIC language

Write a program that will give outputs like the half adder, using only the logic functions you have on your microcomputer (probably only OR, AND, and NOT).

Extension: make a full adder.

EXPERIMENT C13 Making pulses

digital electronics kit with power supply
capacitor } (*1000 μF and 560 Ω are suitable for TTL;*
resistor } 47 μF and 10 kΩ for other gates)
leads

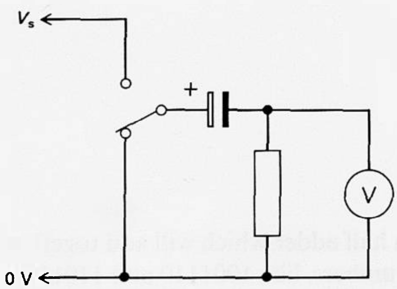


Figure C41

Sketch a graph of the way in which V varies with time when the switch in the circuit shown in figure C41 is moved from 0 V to V_s.

How would you expect a NOT gate to behave when connected to this circuit? Test your prediction. The circuit you need is shown in figure C42.

The circuit shown in figure C42 made a lamp that was normally on go off for a short period. Devise a circuit that will make a lamp that is off go on for a short period.

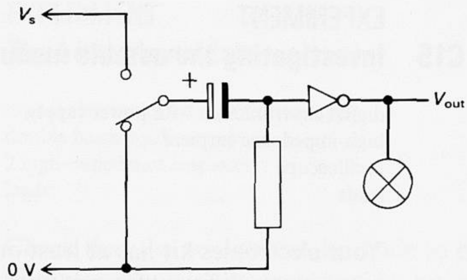


Figure C42

EXPERIMENT
C14 The astable circuit

digital electronics kit with power supply
capacitors } see note to experiment C13
resistors }
leads

C14a What happens in the circuit of figure C43 when the input is switched from 0 V to V_s? Can you explain why this happens? What will happen if the output from the last stage is sent back to the input of the first?

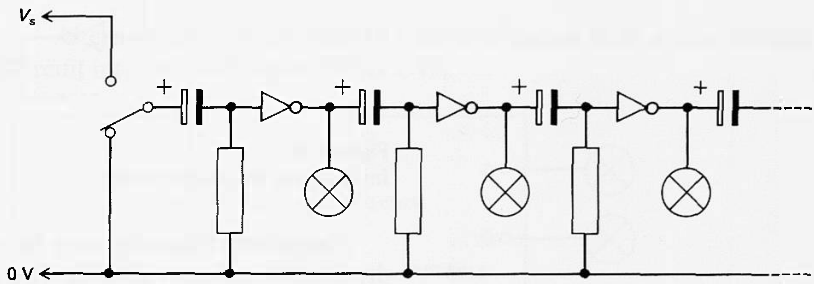


Figure C43

C14b Set up the circuit shown in figure C44. If nothing happens initially, try shorting one of the capacitors momentarily with a flying lead.

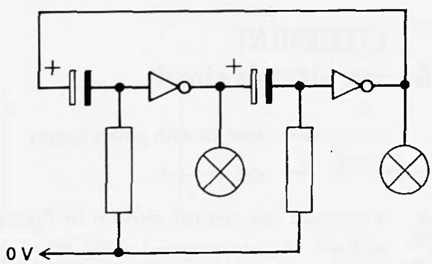


Figure C44

EXPERIMENT
C15 Investigating the astable module

digital electronics kit with power supply
high-impedance earpiece
oscilloscope
leads

Your electronics kit has at least one astable module. Its internal circuit may be very different from your astable circuit, but it is controlled in the same way with an *RC* circuit. The modules vary in the way in which they are controlled, so you will need to consult the manufacturer's data or ask your teacher to find out how to set up your module.

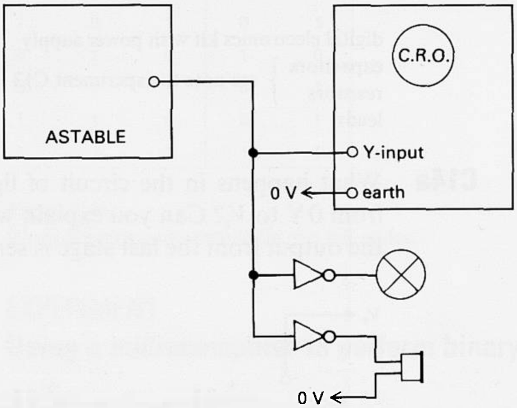


Figure C45
Investigating the astable module.

The astable frequency may be varied over a wide range and used to drive many different circuits. You may be able to get a frequency low enough to see the indicator flashing, and you should certainly be able to get the frequency high enough to produce an audible note in the earpiece. It is good practice to connect a gate between the astable module and anything that you use it to drive, so that the load does not affect the astable module (figure C45).

EXPERIMENT
C16 The bistable circuit

digital electronics kit with power supply
leads

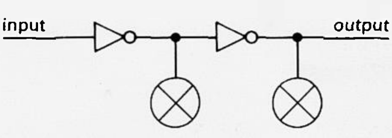


Figure C46

Connect the circuit shown in figure C46. What happens when the input is low? What happens when the input is high?

Connect the output to the input. What happens? How can you change what has happened?

EXPERIMENT

C17 The bistable module

digital electronics kit with power supply
double beam oscilloscope
2 high-impedance earpieces
leads

C17a Check that the module can be made to behave in the same way as the bistable circuit in experiment C16 by connecting each input in turn momentarily to V_s (figure C47). For what could you use this circuit?

C17b What happens to the state of the outputs when the clock input is moved between 0 V and V_s? It helps to use an electronic switch to make these connections (figure C48).

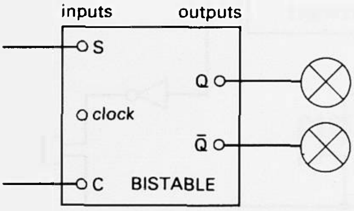


Figure C47
The bistable module.

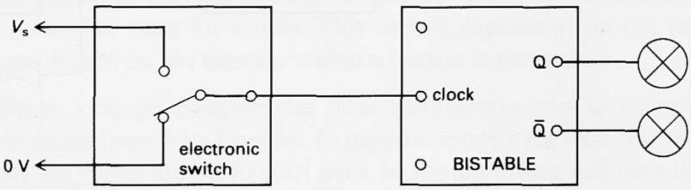


Figure C48
Investigating the clock input.

Alternatively, you can feed in a series of pulses from a slow astable circuit into the clock input (figure C49).

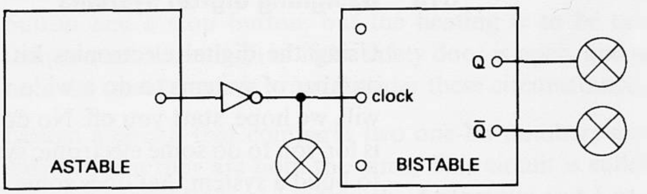


Figure C49
Investigating the behaviour of the bistable module.

Compare the astable module's output with the output from the bistable module. What do you notice?

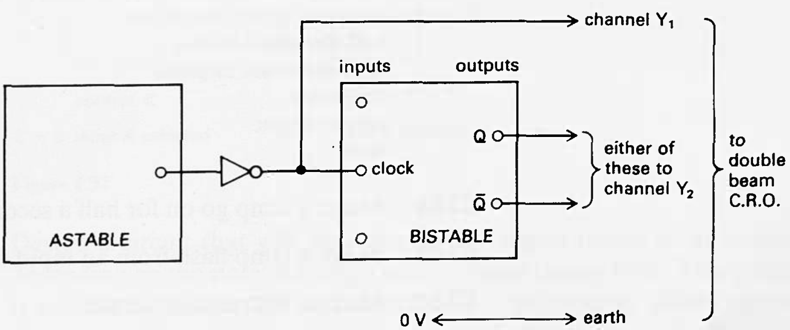


Figure C50
Monitoring input and output of a bistable module.

C17c A double beam oscilloscope can be used to monitor the input and the output of the bistable module as shown in figure C50.

Think of another use for the bistable module.

Why does figure C50 show a gate between the astable module and the input to the bistable module?

C17d Set up the circuit shown in figure C51. Listen to the audible outputs produced in the two earpieces. What do you notice? Give an explanation for what you hear.

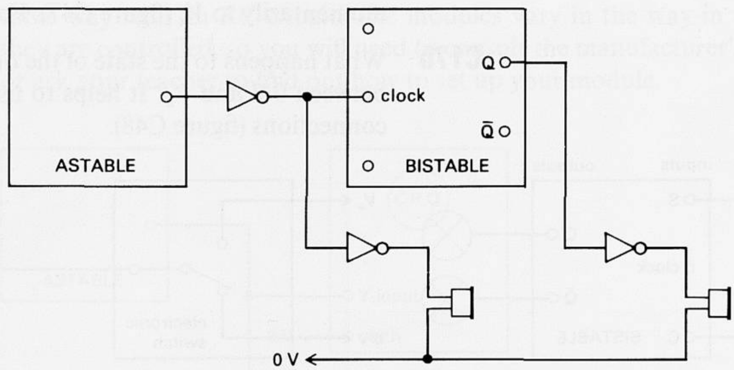


Figure C51
Investigating the effect of the bistable module at an audio frequency.

EXPERIMENT
C18 Designing digital systems

Using the digital electronics kit it is possible to design a very large number of systems to do a wide variety of jobs. The suggestions below will, we hope, start you off. No doubt you will think of others. The idea is for you to do some electronic systems engineering of your own, trying to build a system that does some interesting and potentially useful job.

Of course it is important for you to have a plan for your solution before you start connecting up any circuit.

Some or all of the following apparatus may be required:
digital electronics kit with power supply
various capacitors (between 10 μF and 10 000 μF)
resistance substitution boxes
light-dependent resistor
high-impedance earpieces
thermistor
aerosol freezer
leads

C18a Make a lamp go on for half a second.

C18b Make a lamp flash from an input falling from V_s to 0 V.

C18c Make a Morse code sender.

C18d Make a bleeper that emits an audible pulse of sound when a button is pushed.

C18e Make a lamp give six flashes in a row.

C18f Make a device that emits six audible pips in a row.

C18g Make a device that emits a warning tone when a thermistor's temperature becomes high. Then try a warning of low temperature.

C18h Use a light-dependent resistor to produce a warning tone when the light level is low. Then try high.

C18i Make a system that can be used with a counter to time the interval between two successive pushes of a button.

C18j Make a human response timer to measure the time a person takes to respond to a lamp coming on (or a tone sounding), by pressing a button.

C18k Make a monostable circuit. Halfway between a bistable and an astable circuit is one that has one stable state but may be momentarily switched to another state for a time. This time is dependent on the values of *C* and *R*, not on the time for which a button is pressed.

C18l Make a binary counter. Use three bistable modules to make a counter to count from 0 to 7 pulses. Extension: modify the first circuit so that if all the lamps are on to start with, incoming pulses will turn them off in the binary sequence from 7 down to 0.

C18m Make a digital frequency meter that displays the frequency of a supply in digital form (binary form using the electronics kit, in scale of ten using a counter/scaler).

C18n Make a safety interlock system for a furnace which is to have a start button and a stop button; but the heating is to be turned off if the temperature is too high or if the safety door is open, and must not come on if the start button is pressed under these circumstances.

C18o Design a circuit that compares two one-bit numbers and gives a high output when they are both the same. This circuit is called a 'comparator', and is usually found within the Arithmetic and Logic Unit (ALU) of a microprocessor.

C18p Extend your solution to C18o to compare two two-bit numbers.

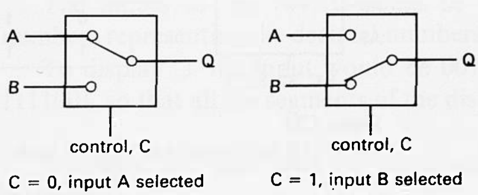


Figure C52

C18q Design a circuit that will pass one of two digital inputs to an output depending on the state of a single control input (figure C52). This circuit is called a 'data selector' or 'multiplexer'. A multiplexer allows signals from several lines to share a single output line; for example, it allows the

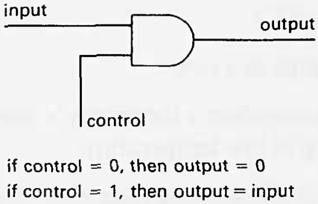


Figure C53
AND gate used as a switch.

28 segments of a four-digit display to be controlled with 8 rather than 29 lines (one for each digit and one common to all digits).

Hint: an AND gate may be used as a switch as shown in figure C53.

The 74LS157 is a multiplexer which has four pairs of inputs and four outputs (figure C54).

When SELECT is low the A inputs are passed to the output. SELECT high passes the B inputs to the output. This particular integrated circuit has another input, ENABLE, that allows the user to disable the device totally if necessary. When the ENABLE is high all outputs are forced low.

Notice that only one control line is needed to select one of two sets of inputs.

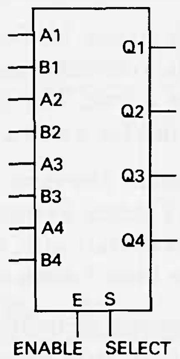
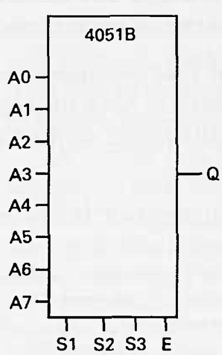


Figure C54
The 74LS157 multiplexer.

The CMOS 4051B is an eight-channel multiplexer. One of the eight one-bit inputs is selected and connected to the output. Three select lines are now required. Each can be high or low, giving a total of $2^3 = 8$ combinations as the truth table in figure C55 shows.



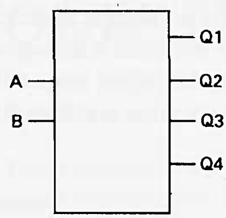
SELECT S1	S2	S3	input appearing at Q
0	0	0	A0
1	0	0	A1
0	1	0	A2
1	1	0	A3
0	0	1	A4
1	0	1	A5
0	1	1	A6
1	1	1	A7

Figure C55
The 4051B multiplexer and its truth table.

The ENABLE, E, on this chip performs the same function as the ENABLE on the 74LS157. When it is high the output is held low.

C18r Design a circuit with two inputs and four outputs that obeys the truth table in figure C56. Notice that only one of the outputs is high at any time.

The inputs 00, 01, 10, 11 are the binary equivalents of 0, 1, 2, 3; that is, the circuit is decoding the binary input.



inputs		outputs			
A	B	Q1	Q2	Q3	Q4
0	0	1	0	0	0
1	0	0	1	0	0
0	1	0	0	1	0
1	1	0	0	0	1

Figure C56

Hint: Note that Q4 = A AND B which means you can start your design as shown in figure C57. Look for similar relationships between the other outputs and A and B.

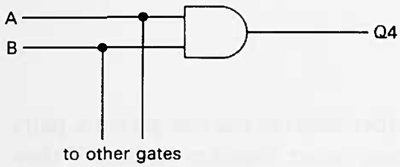


Figure C57

This circuit is called a ‘decoder’. It is used in microcomputers and in many other digital circuits. A very common application is activating a 7-segment LED display. An integrated circuit commonly used to do this is the TTL 7447A. The 7447A decodes four input lines to seven outputs to produce the pattern required to activate the display. With four input lines, $2^4 = 16$ different combinations of four inputs are possible, but to represent the decimal numbers 0 to 9, only ten combinations need to be decoded.

The circuit of a 7-segment display and the layout of the segments are shown in figure C58.

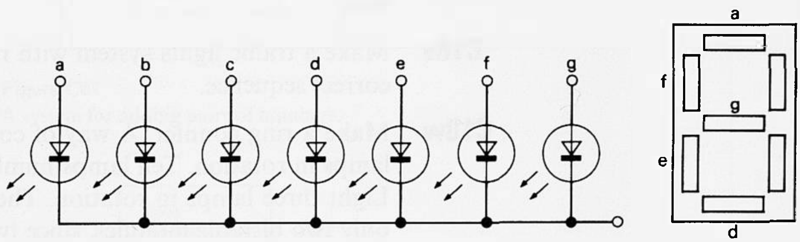


Figure C58
A seven-segment display.

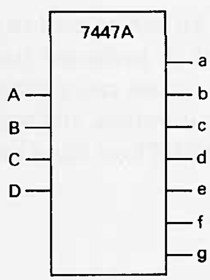


Figure C59
The 7447A decoder.

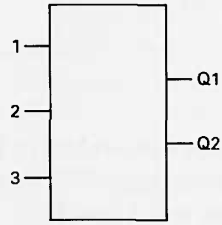
So, if we wished to show the figure ‘3’ for example, segments a, b, c, d, and g would have to be activated.

The inputs to the 7447A would be the ‘binary coded decimal’ numbers representing the decimal numbers 0 to 9, that is 0000 to 1001.

To display ‘3’ the input would be 0011 and the output would be 1111001, so that all the segments of the display except e and f would be on.

Decoders are also used in microcomputers to select blocks of memory.

C18s The opposite of a decoder is an 'encoder'. The problem below illustrates the idea. Design a circuit which produces the correct binary equivalent of a decimal number when one of the keys 1, 2, or 3 is pressed. A block diagram and truth table are shown in figure C60.



inputs			outputs	
1	2	3	Q1	Q2
0	0	0	0	0
1	0	0	1	0
0	1	0	0	1
0	0	1	1	1

Figure C60
An encoder.

C18t Make a coincidence detector. In an experiment in nuclear physics, pairs of counts from decays of particles may occur together in time if they have a common origin. Devise a system to indicate if two pulses fall within a fixed time of each other.

C18u Make a pulse delay system. Start by extending a square pulse by a fixed time. Then add to the system to remove the front part of the extended pulse and so produce a pulse like the original one but delayed by a fixed time.

C18v Make a traffic lights system with red, amber, and green flashing in the correct sequence.

C18w Make a ring counter. A way of counting pulses is to make them light lamps in rotation. Ten lamps numbered 0 to 9 make a decade counter. Light three lamps in rotation. Then try four (which can be done with only two bistable modules, since two bistable modules will count up to four in binary arithmetic).

C18x Playing tunes. The digital electronics kit can be used to play tunes. One can either make a simple organ with a keyboard (switches or push buttons) controlling a series of notes, or one can arrange that a system itself selects notes of the proper pitch, duration, and sequence to play a tune. Try something like the first bars of 'Three blind mice'.

QUESTIONS

Systems

These questions are about systems, and the usefulness of thinking about complicated electronic circuits as systems made up of interconnected parts.

1(P) A system is a collection of parts, in which each part has a definite job to do, all the parts acting together to do whatever task is required of the system.

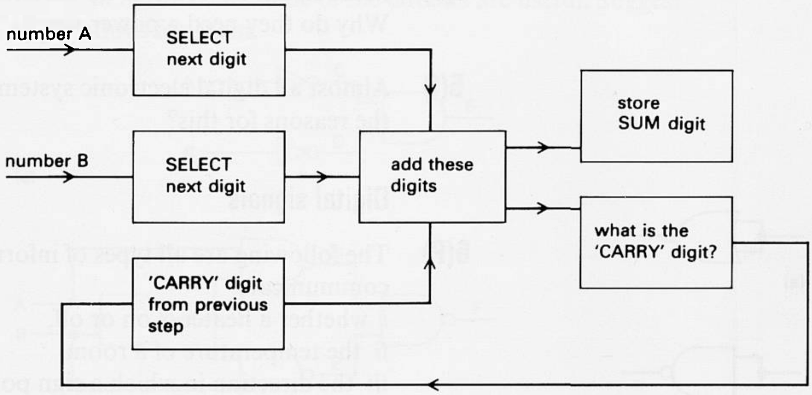


Figure C61
A system for adding pairs of numbers.

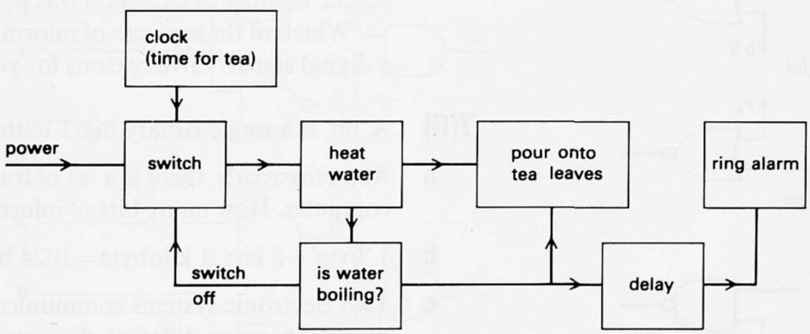


Figure C62
A system for making tea.

To illustrate the idea, figure C61 shows a system for adding up numbers, while figure C62 shows one for making tea automatically.

a Explain how the system for adding numbers works. That is, say what happens step by step. You need not say how a machine might achieve each step: that is another problem.

b Explain how the tea-making system works.

c Draw a similar system for one or more of the following things:
Controlling cars at a pedestrian crossing.
A 'pop-up' toaster.
An automatic washing machine with control of water temperature, washing time, and spinning time.

2(I) Suppose you are listening to a song on a record player; trace the series of things which have happened to the song signal on its way to you.

3(E) Write an essay about 'systems'. What are they, what do they do? What does the word system mean? How can we use the concept of a system?

4(E) Most electronic systems have an input, an output, and a power supply. Why do they need a power supply? What about other systems?

5(I) Almost all digital electronic systems use the binary system. What are the reasons for this?

Digital signals

6(P) The following are all types of information you might want to communicate:
i whether a heater is on or off,
ii the temperature of a room,
iii the direction in which a sign points at a junction,
iv the magnitude and direction of an electric current,
v the number of pages in this book,
vi the area of this page,
vii the number of letters on this page.
Which of these pieces of information could easily be transmitted by a digital signal? Give reasons for your answers.

7(R) A 'bit' is a single BInary digiT (either 0 or 1).

a At a crossroads, there is a set of traffic lights controlled by a central computer. How many bits of information need to be communicated?

b 1 'byte' = 8 bits. 1 kilobyte = 1024 bytes. Why is it 1024 and not 1000?

c Two electronic systems communicate with each other in chunks of one byte. How many different characters can they communicate?

d How many bytes of information are there on this page?

Logic gates

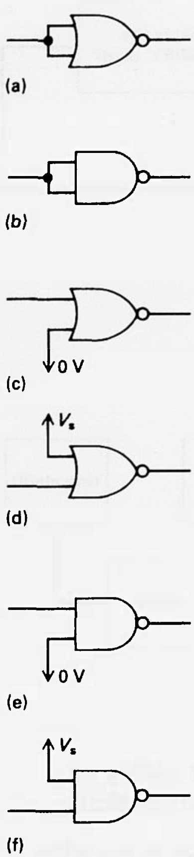


Figure C63

8(P) Figure C63 shows some simple applications of NOR and NAND gates. Draw a truth table for each circuit and describe what each will do.

9(L) Suppose two inverters and a NOR gate are connected as shown in figure C64. Copy and complete the table shown in figure C65, showing what the outputs are for various inputs. What might such a system be used for? Test your answer in the laboratory.

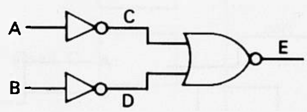


Figure C64

inputs		outputs		
A	B	C	D	E
0	0	1	1	0
1	0	0		
0	1			
1	1			

Figure C65

10(P) Draw up your own tables to describe the behaviour of the circuits shown in figure C66. Some of the circuits are useful. Suggest applications for them.

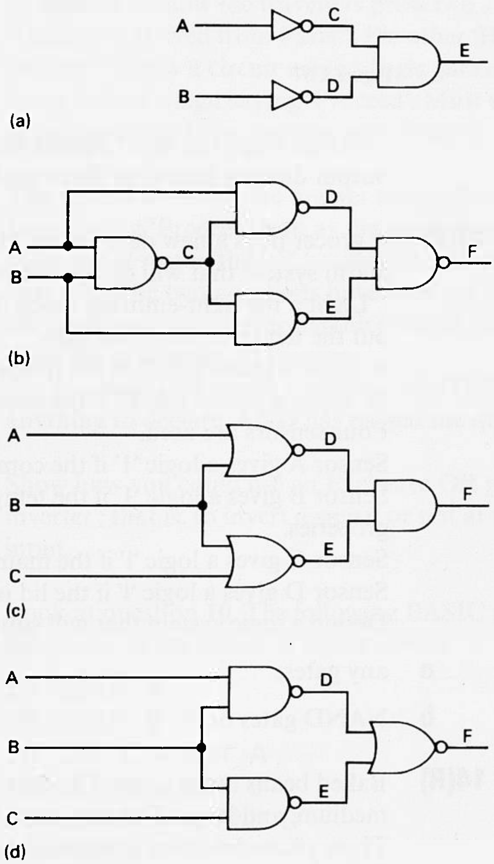


Figure C66

11(P) Design a digital circuit that gives a high output when two signals are the same (that is, both high or both low).

12(P) Figure C67 shows several two-input gates. In each case a pair of signals is fed into the inputs of the gate. For each gate sketch the signal you would expect to see at the output of the gate.

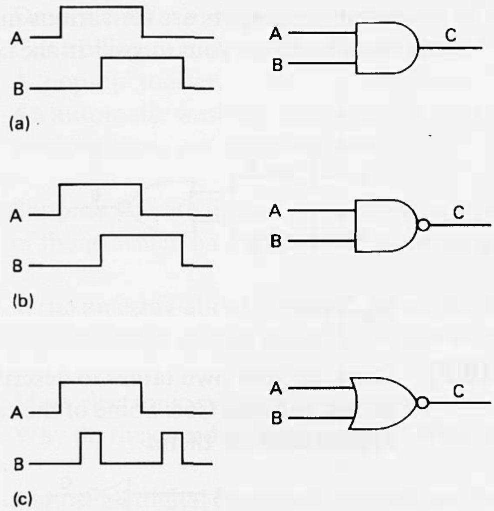


Figure C67

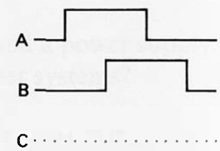


Figure C68

Hint: Copy the input signals shown in figure C67, and draw the output directly below, as illustrated in figure C68.

13(P) A grocer buys a new deep freeze. He wishes to make a battery-powered alarm system that will do the following:
i Light a red light-emitting diode (L.E.D.) if the compressor is running but the temperature is too high.
ii Light a green L.E.D. if the temperature is low and the lid is open.
iii Light a yellow L.E.D. if the mains fails.
Four sensors are used.
Sensor A gives a logic '1' if the compressor is running.
Sensor B gives a logic '1' if the temperature is too high to store groceries.
Sensor C gives a logic '1' if the mains is on.
Sensor D gives a logic '1' if the lid is shut.
Design a logic system that will solve the grocer's problem using

a any gates;

b NAND gates only.

14(R) Baked beans are produced in cans of three different sizes: small, medium, and large. The cans have to be sorted ready for packaging. Three photodetectors are available that give a logic '1' output when a light shines on them; otherwise they are at logic '0'. They could be arranged on either side of a conveyer belt, as in figure C69, so that the cans would cut the light incident on one or more photodetectors.

Design a system that will light an indicator if a medium size can passes but not a small or large can.

15(P) Suppose the customs officials at an airport decide to allow travellers through without inspection as long as they say that they have nothing

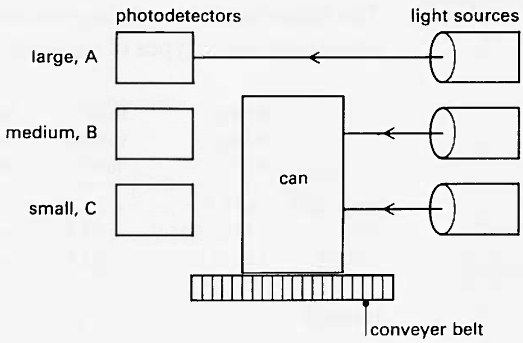


Figure C69

to declare, and that they have not flown in from Paris. The decision is to depend on how the travellers press two switches. One is labelled 'Have you arrived from Paris?', the other 'Have you anything to declare?'. Draw a circuit using a logic gate and two switches to light a lamp behind a sign saying 'Proceed'. Must the switch position that corresponds to V_s be marked 'yes' or 'no'?

16(P) The system shown in the answer to question 15 has the defect that the lamp saying 'Proceed' is lit as the passengers walk up to the switches if these are at rest in the 0 V position. Add a third switch to the system so that, after the two questions have been set, the sign only lights up as the passenger walks over the third switch (hidden in the floor), closing it, on his or her way to the sign.

You have then made a system, 'NEITHER from Paris, NOR with anything to declare, AND has passed the questioning point'.

17(P) Show how you could use an Exclusive OR gate as an 'optional inverter'; that is, to invert a signal or not at the control of another input.

18(P) Look at question **10**. The following BASIC program has the same behaviour as the circuit in figure C66(a).

```
10 INPUT A
20 INPUT B
30 LET C = NOT A
40 LET D = NOT B
50 LET E = C AND D
60 PRINT
70 PRINT E
80 PRINT
90 GOTO 10
```

a Enter the program into a microcomputer and check that it gives the answer you expect.

b Write similar programs to behave in the same way as the circuits in figures C66(b) to (d).

19(P) The following table summarizes some of the most important specifications for three types of logic kit.

	Supply voltage, V_s	Input voltage 'low'	Input voltage 'high'	Output voltage 'low'	Output voltage 'high'
'basic unit'	5 to 6 V	<0.5 V	>1.5 V	≈ 0.1 V	≈ 4.7 V
TTL	4.75 to 5.25 V	<0.8 V	>2 V	<0.2 V	>3 V
CMOS	3 to 15 V	$<0.2\ V_s$	$>0.8\ V_s$	$<0.01\ V_s$	$>0.99\ V_s$

Table C3

a You have an unmarked electronics kit. What power supply voltage would you use at first to try it? Explain your answer.

b Why is it important that all the figures in column 4 (output voltage 'low') are less than the corresponding figures in column 2 (input voltage levels 'low')? There is a similar relationship between another pair of columns. Which pair?

c The figures in the last two columns are specified in different ways for each of the systems. Explain why this is so.

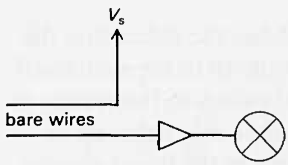


Figure C70
A rain detector.

20(P) The circuit shown in figure C70 is a rain detector. The indicator lights up when rain falls on the bare wires.

a Explain why the circuit works.

b Why is the logic gate necessary? Why is it not adequate to use a circuit such as that shown in figure C71?

c When pure water is used instead of rain water, the indicator fails to light. Why is this so?

d The system is to be modified to control the pump filling a water tank. The pump should switch off when the water level gets high enough. How would you modify the circuit? What extra components would you need?

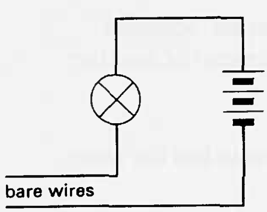


Figure C71

21(P) Figure C72 shows two arrangements for monitoring the temperature of a chemical processor. Both thermistors have a resistance that decreases with temperature.

a Which circuit warns when temperatures are too high? Which protects against temperatures that are too low? Explain your answer.

b The circuit shown in figure C73 combines both functions. Explain how it works. If an OR gate were used instead of the NOR gate what difference would it make to the operation of the circuit?

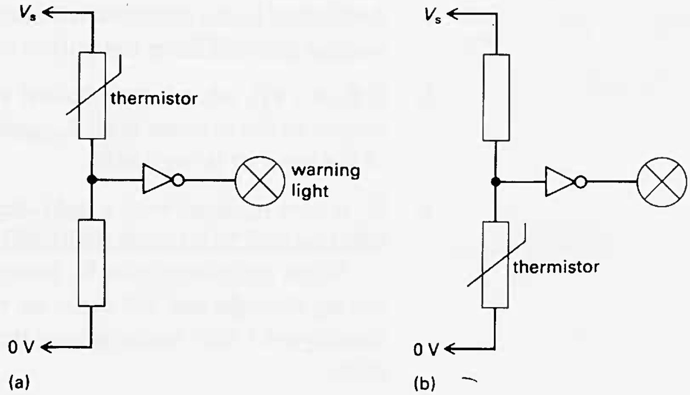


Figure C72
Circuits for monitoring temperature.

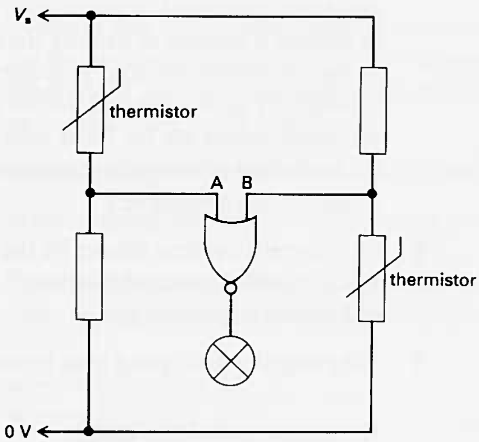


Figure C73
A temperature warning circuit.

22(R) To answer this question and the following one, you need to apply what you know about potential dividers, that is, arrangements of resistors that are used to fix a voltage at a particular value at a point in a circuit (Unit B, ‘Currents, circuits, and charge’).

The circuit diagram in figure C74 shows two resistors being used to control the input to an inverter. The voltage transfer characteristic for the gate is also shown.

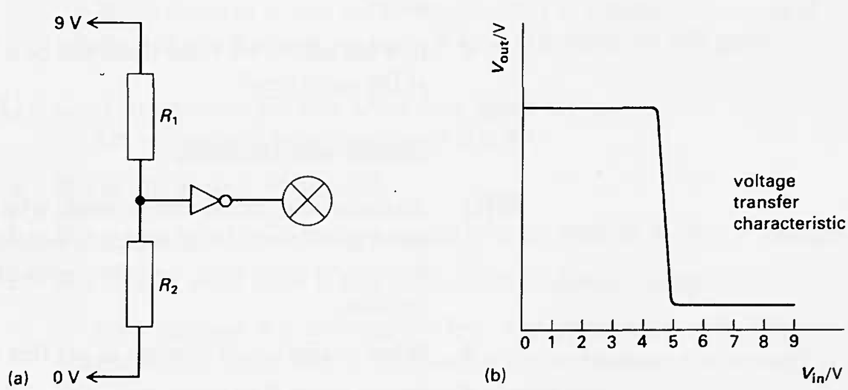


Figure C74

a According to the characteristic curve, what is the smallest input voltage that will keep the output of the gate low?

b If R_2 is 1 kΩ, what is the smallest value that R_1 can have to keep the output of the inverter low? Assume that the current drawn by the input of the inverter is negligible.

c R_1 is now replaced with a light-dependent resistor (L.D.R.) which has a resistance of 500 Ω in daylight and 10 kΩ in darkness.

What resistance must R_2 have so that the indicator will be off during daylight but will come on when the resistance of the L.D.R. rises above 1 kΩ? Again, ignore the effect of any current drawn by the gate.

d If you set about building this circuit using the value of resistor that you have calculated in part **c** you would probably have some difficulty in finding a resistor of exactly that value: it would be quite expensive to buy. Resistors are sold in *preferred values* to a specified *tolerance*. Commonly used tolerance values are 5 % and 10 %. Find out what the preferred values are for these tolerances. (A good source of information for such data is an electronics components catalogue such as the RS Components catalogue.)

e Suppose the current drawn by the gate itself is not negligible. How would it affect your calculations? Assume that the gate draws a current of 1 mA as a worst case.

f Why might it be a good idea to use a variable resistor for R_2?

Arithmetic with logic gates

23(R)a Draw the truth table for a 'half adder'.

b Draw the truth table for a 'full adder'.

c What is meant by the 'SUM' and 'CARRY' terms?

24(R)a Draw a 'half adder' using NOR gates.

b Show how two half adders can be connected together to make a 'full adder'.

c In a full adder, why can there not be a 'CARRY' from both half adders at the same time?

Circuits with feedback

25(L) An electronic circuit can be made which behaves as follows. When the input goes from low to high, the output goes from high to low, stays there for a short time, and then goes high again. Figure C75 illustrates the idea.

a What circuit could you use to get this result?

b Two such circuits are put in a row as in figure C76.

What does output 2 do when input 1 goes from low to high?

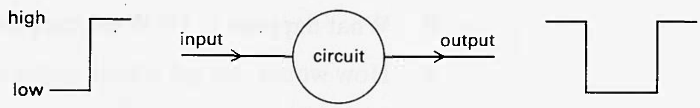


Figure C75

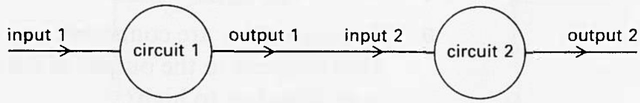


Figure C76

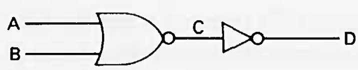
c If output 2 is joined to input 1, what happens?

26(P) Suppose you have a signal source whose output goes from 0 V to V_s for five seconds, returns to 0 V for five seconds, and so on, indefinitely. How could you use logic gates with such a supply to drive a lamp, perhaps a buoy at sea which

a flashes, going on for one second every ten seconds?

b occults, going out for one second every ten seconds?

27(L) Figure C77 shows an inverter connected to a NOR gate. Complete the table giving the output of the combination.



A	B	C	D
0	0	1	
0	1	0	
1	0		
1	1		

Figure C77

Write down in words the conditions that D is high (1) in terms of whether or not A and B are high. Why is this called an OR gate?

28(L) Look at question 27. Join D to A in figure C77.

Let us consider what happens if B is low.

a If A is low as well, what is C?

b If A is low, what is D? If A is low and D is fed back to A, does A change?

c If A is high, what is D? If D is fed back to A, does A change?

Now suppose A is low and B is low, with D fed back to A. The system will sit there, with A kept low by D just because A is already low. Now think of B being made high. C goes low.

d What happens to D? What happens to A? What happens to the circuit?

e How would you get it back to the condition with A low?

f Why is this system called bistable?

29(L) Look back at questions **25** and **28**.

a If two inverters are connected in a row, the first feeding the second, what happens to the output of the second if the input of the first starts to go from low to high?

b Now suppose that the output is fed back to be the input of the first. If the input of the first starts to go high, what happens to it next? What happens later? What happens in the end?

This is called *positive feedback*; a change to the system drives the system further in the same direction.

30(E) Suppose the small local shop looks like running out of chocolate, and there isn't another shop nearby. Naturally, some people hasten to buy what they can before it is too late. Seeing this happen, others do the same. What happens? What has this to do with question **29**?

Many economic systems are like this. What might happen if one market trader cut the price of his apples one day? How might his customers react? How might his competitors react? What will happen in the short term? What will happen in the long term?

31(R) Figure C78 shows a crude burglar alarm system. If any of the door or window switches are closed, the alarm sounds.

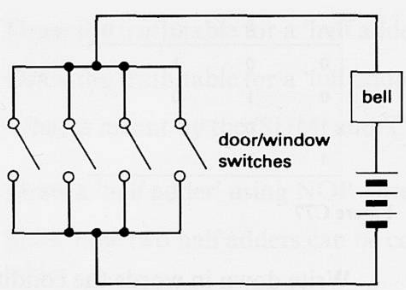


Figure C78

Figure C79 shows an improved system. In this circuit, the alarm will sound if one of the door or window switches is opened.

a Explain how this arrangement works.

b Why is it an improvement on the first arrangement?

c A practical arrangement uses the circuit shown in figure C80. In what way is this a further improvement?

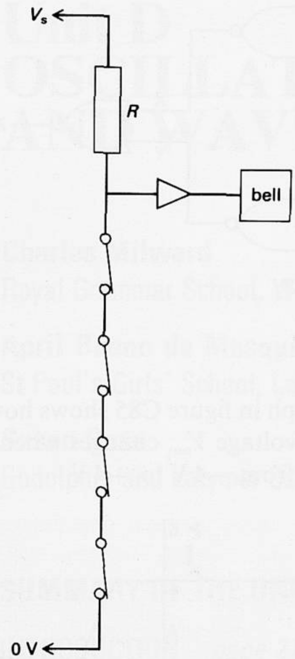


Figure C79

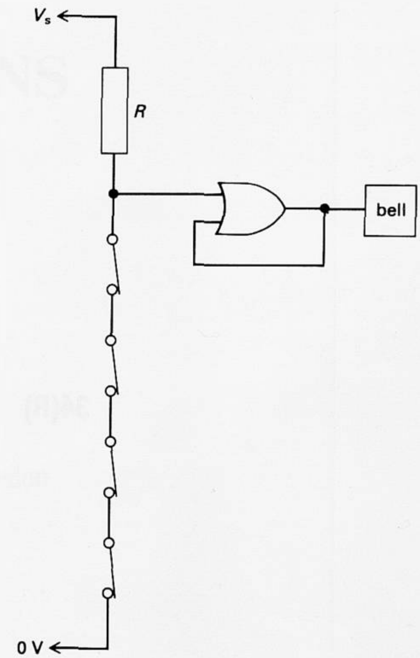


Figure C80

Logic gates

32(R) A NOR gate has two inputs, p and q. The output of the NOR gate and a third input, r, are the inputs to an AND gate (figure C81).

Which one of the following sets of values of the inputs p, q, and r will result in the output of the AND gate being 1?

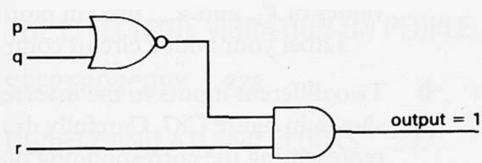


Figure C81

	inputs		
	p	q	r
A	0	0	0
B	0	0	1
C	1	0	0
D	1	1	0
E	1	1	1

Figure C82

(Coded answer paper, 1979)

33(R) The four inputs, 1 = high and 0 = low, to a pair of two-input NOR gates are as shown in figure C83.

Which of **A** to **E** is the correct combination of the values X and Y at the input to the third NOR gate, together with the output Z of the third gate?

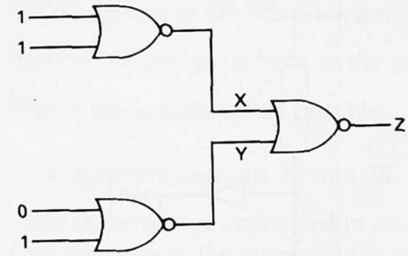


Figure C83

	X	Y	Z
A	0	0	0
B	0	0	1
C	0	1	0
D	0	1	1
E	1	0	1

Figure C84

(Coded answer paper, 1981)

34(R) The graph in figure C85 shows how, for a self-contained inverter, the output voltage V_{out} changes when the input voltage V_{in} is varied over a range from -4 V to $+4$ V.

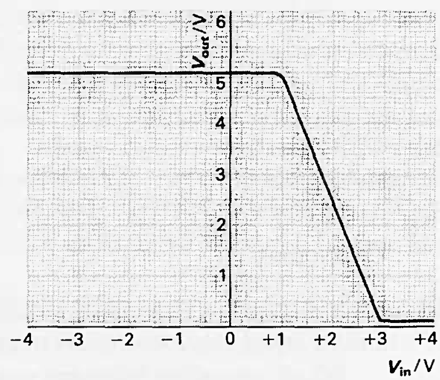


Figure C85

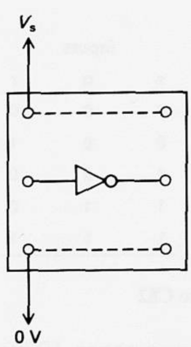


Figure C86

a The inverter is shown in figure C86. Copy the drawing and add the input and output circuits which could have been used to obtain the values of V_{in} and V_{out} used in plotting the graph in figure C85.
Label your added circuit components.

b Two different inputs to the inverter are represented on the pair of axes shown in figure C87. Carefully draw graphs, on appropriate axes, representing the corresponding outputs from the inverter.

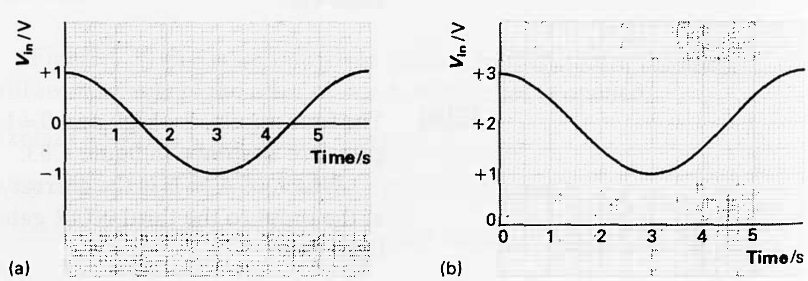


Figure C87

(Short answer paper, 1980)