REVISED

NUFFIELD PHYSICS

Teachers' Guide
Years 1 and 2

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ISBN 0 582 04682 3

General Editors
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NUFFIELD PHYSICS TEACHERS' GUIDE YEARS 1 AND 2

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Foreword

In the early 1960s the Nuffield Foundation commenced its sponsorship of curriculum development in the sciences. Specific projects can now be seen in retrospect as forerunners in a decade unparalleled for interest in teaching and learning, not only in, but far beyond, the sciences. Their success can best be measured by their undoubted influence and stimulus to physics amongst teachers—both convinced and not-so-convinced.

The examinations accompanying the schemes of study, which have been developed with the ready co-operation of the Schools Certificate Examination Boards, have provoked change and have enabled teachers to realize more fully their objectives in both classroom and laboratory. The changes continue and the nation is currently engaged in discussion of further alterations to the pattern of examinations. Whatever the outcome, we are confident that these Nuffield studies will continue to make important contributions to the teaching and learning of science. In these volumes we have attempted to produce materials to meet the needs of particular classroom situations. Where curriculum development is not capable of adaptation and renewal, it impedes, rather than encourages, innovation and it commits the very sin it sets out to avoid.

The opportunity for local curriculum study has seldom been greater and the creation of Schools Council and teachers' centres has done much to contribute to discussion and participation of teachers in this work. It is these discussions which have enabled the Nuffield Foundation to take note of changing views, to correct or change emphasis in the curriculum in science, and to pay attention to current attitudes to school organization. We have learned from many, particularly those in the Association for Science Education, who, through their writings, conversation, and contributions and in other varied ways have brought to our attention the needs of the practising teacher and the pupil in schools.

This new edition of the Nuffield physics material draws heavily on the work of the editors and authors of the first edition published in 1966. An immense debt is owed to them. The physics programme was inaugurated in May 1962 under the leadership of Donald McGill. It suffered a severe setback with his tragic death on 22 March 1963, but those who were appointed to continue the work have done so in the spirit in which he initiated it, and in the direction he foreshadowed. He was succeeded as organizer by Professor E. M. Rogers. Together with the associate organizers, John Lewis at Malvern and E. J. Wenham at Worcester, the assistant organizer, D. W. Harding, and the deviser of the *Question Books*, the late H. F. Boulind, the teams of teachers led by Eric Rogers produced teaching ideas that have influenced profoundly curriculum discussions and physics at a time of major educational change.

The new volumes draw in many ways on the original *Teachers' Guides* and *Guides to Experiments* and *Question Books*. Their contribution in providing a firm basis for these further developments is gladly acknowledged here. It is a pleasure to praise the part played by the large number of teachers who have helped in discussion, feedback and persuasion but it is once more to Eric Rogers who, with an extraordinary vitality, has led and completed this work, that we especially record our thanks.

Our thanks go with equal appreciation to Ted Wenham. As well as editing *Teachers' Guide Years 1 and 2* in the new edition and writing the new *Pupils' Text Years 1 and 2*, he has continued to act as a very wise and helpful consultant on all aspects of the programme. His judgement and knowledge have been welcome and essential throughout.

Lastly I should like to acknowledge the work of William Anderson, our Publications Manager, and his colleagues, and of course our Publishers, the Longman Group Ltd, for their continued assistance in the publication of these books. The editorial and publishing contribution to the work of the projects is not only most valued but central to effective curriculum development.

K. W. KEOHANE
Co-ordinator of the Nuffield Foundation
Science Teaching Project

General Editors' Preface

A dozen years ago the Nuffield Foundation, following requests from teachers who suggested changes in O-Level Physics teaching, gave a large grant for studies of needs, development of apparatus and the provision of printed materials to offer a new teaching programme to schools who liked to try it.

The essence of that programme, as it emerged from consultations, visits to schools, discussions in groups of teachers—was a change from teaching hampered by insistence on rote learning towards even more learning for understanding which, it was felt, would provide greater chances of pupils' learning of science being transferred towards long-lasting benefits.

By now, pupils of many schools have tried that programme – we believe with enjoyment and some success. As pupils reached the end of the five years to face an O-Level Examination, the teaching proved justified by the admirably relevant Nuffield Physics papers produced by the Oxford & Cambridge Schools Examination Board (acting on behalf of all Boards). The number of candidates for that Nuffield O-Level Physics Examination is now over 20,000 each year.

Those Nuffield papers were set with the aim of testing the teaching and learning that we suggested; and they received sympathetic marking which looked for understanding in candidates' answers.*

Many teachers have followed some general suggestions:

1 Let pupils work in the lab in small groups, often pairs, and leave them alone to make their own mistakes and find their own solutions, except where rescue is needed. That seems to us near to professional science.

2 Use stimulating questions as principal learning aids to encourage discussion, reasoning, and imagination.

In making the revision for this new edition we received a general directive from the Foundation; that we should try to maintain the same standard of enquiry, and learning of science for understanding, and not change the programme in a way that would 'lose the Nuffield spirit'. The Foundation recognized the changes in school structure but considered that other programmes, such as Nuffield Secondary Science, provide better for other levels of treatment than a heavily diluted version of our programme could do.

We started the revision by consulting some 200 teachers, some of them in person, many by profuse enquiry forms. We also visited a considerable number of schools to see Nuffield classes in their present form. Again, those visits influenced us very profitably in our revision.

We changed Dr Henry Boulind's excellent Questions for thinking and understanding to simpler wording, but retained their essential enquiry. In response to pleas from teachers, and to the needs of the new school structure, we added Progress Questions to provide a different and easier approach.

Our most important change of all in the revision has been the production of the *Pupils' Text* in four volumes, to provide young scientists with help for experiments and some discussions of ideas, also thinking questions and progress questions. Thus for many pupils this book should act as a complete substitute for work cards.

On behalf of teachers and pupils who will use these books, we owe thanks to many people: to our consultant teachers, without whose advice we could not have envisaged the needs of the project; to Professor R. A. Becher, who was our chief inspiration and guide in the original project, to whom we still turn for wise advice; to Professor K. W. Keohane as our co-ordinator with counsel

*Two small examples may illustrate that:
i The Board prints on the front of the Examination paper all the formulae likely to be wanted – this is an assurance to both teachers and pupils that just 'memorizing formulae' is not so important. Candidates realize that memorizing definitions and formulae is not very profitable. On the other hand, the Examiners expect a candidate to understand the origin and uses of some formulae and their limitations – like a capable craftsman. And they expect a candidate to be able to describe physical quantities and relationships in his or her own words.
ii In marking scripts for O-Level, the Nuffield Examiners have not felt themselves restricted by a fixed marking scheme. They read with a flexible attitude, looking for good knowledge, imagination, and interesting suggestions too – which they award with bonus marks.

concerning Physics and teaching and people; to John Maddox, Director of the Foundation, for past interest and care, and now special encouragement. Both teachers and pupils will owe much to the five teachers who constructed the Progress Questions – forged and tempered them. Anthea Arnold, Margaret Fawcett, Reinet Fremlin, Gwen Jones, and Hilda Misselbrook.

We would also like to thank the following: Michael Spincer of the Longman Group who gave much valuable advice at various stages in the planning and production of these books; the editors who saw them through the stages of production, Hendrina Ellis and Richard Shaw; our artist, Rodney Paull who is responsible for all the illustrations; the designers and art directors, Ivan and Robin Dodd; and Deborah Williams who carried out the picture research.

Eric M. Rogers, E. J. Wenham
General Editors

Concerning the nature of things

'The richness and diversity of our world; solid, liquid and gas; crystal and powder; metal and non-metal: with physical distinctions made by volume and density; compression and stretching (elasticity and flow); temperature and the effect of heating, including expansion and change of state. The light which studying these physical changes throws upon the underlying atomic and molecular structure and mechanisms.'

Donald McGill 1963

In his last outline of the Physics programme of the Nuffield Science Teaching Project, Donald McGill wrote this at the head of his first page. It states our aim as clearly as ever, although there have been changes of order; and it is reprinted here as a tribute to the spirit and the vision with which he guided the programme.

Preface for the first two years

These are years of gaining acquaintance with materials and their properties and behaviour, and instruments, and the way scientists do things, and just a little of the way scientists talk. They are Years of seeing and doing, with very little to be learnt by heart. But, in the second of the Years, there is a little more emphasis on organizing the knowledge in a scientific way – by looking for general rules of behaviour and by using imaginative models.

Where the children will start, and how far they will go, must depend on what they have done and heard before, in school or at home, as well as on abilities and interests. Since we want them to keep their enthusiasm and enjoy learning science – and not be bored by things that are too easy or too familiar, or puzzled by arguments that run too fast or too far – we should be wise to do our own showing-and-explaining quickly, then leave pupils to do their thinking about it and learning from it at their own pace. Then they will, we hope, develop a feeling that they understand some pieces of science. Some pupils will ask us for further explanation, and will then learn well; but others, who do not understand from the short story and so do not want to ask more, are not ready to learn that piece of science – at best we could only drill them into learning formal statements for examinations.

On the other hand, those things that the children do themselves will last in memory, but the doing needs a long elastic stretch of time. The children are, in a sense, being young scientists when they do class experiments. Just as professional scientists are not given a book of instructions or required to get the 'right answer', children – if they are to understand how science is done – need to be left alone, with encouragement but no more instructions than are absolutely necessary. The teacher can start the question, make suggestions, offer criticisms, give encouragement, but he should not hurry children through, or insist on a 'right' result.

Finishing each experiment at the right instant (with a proper record of it) and hurrying on to the next experiment with full instructions may look efficient, but it has not produced a generation of educated laymen who enjoy the feeling that they understand physics; nor has it given future scientists the most fruitful image of science to start with. And yet class experiments *can* play a very important part in these Years – as in all our programme. They not only provide new knowledge; they can give children personal experience of working as scientists. In the latter role they are essential in our course. For class experiments to give that experience, we must allow children plenty of time: time to arrange their experiment; time to try it out; time to change things round to make it go better; above all, time to enjoy working, with a feeling that it is their own experiment. In fact the wise teacher will often reply, when a child asks whether his experiment is going well enough, or whether something is 'right', 'It's *your* experiment. You are the scientist today.'

For such work in class experiments, it is very important to have plenty of apparatus and materials available. In later Years we can tell pupils they should ask for extra equipment that they need, or even fetch it from the proper place. But here we are dealing with strangers in this land of physics, so we must make the general topography obvious. The only piece of equipment that should *not* be offered is a sheet of printed instructions.

Instruments such as a magnifying glass and a microscope should come in as things to use and not (at this early stage) as things with a mechanism to be explained – we should remember how we use a stop-watch without opening it and without teaching anything about S.H.M. or compensated balance-wheels.

When children do their experiments on their own, they take a long time, much longer than a capable physicist would expect. That is worth while, because it is the children's chance to 'do science'; but we must provide the needed time. We do that by having fewer class experiments. We omit some of the usual ones, and convert others to demonstrations – what does that matter, when our aim is to give genuine experience? So we offer a few long class experiments and a number of very short ones – for a quick glimpse with direct experience – and a number of demonstrations. Sometimes a new piece of apparatus, such as a dynamic model of gas molecules in motion, can save a lot of teaching time.

Teachers should consider that they are encouraging young scientists to make their own gains in knowledge, and a little in skill. And they should remember that there is no piece of material in the syllabus which cannot be learnt very easily later on if it is missed now. (It is our pupils' progress in building a general attitude and sense of understanding that will need the full five Years.) So our motto for these early Years is not 'training in skills, and collecting information' but rather 'gaining a sense of knowledge by seeing and doing, and using instruments for finding out'.

At this stage of the course, instead of giving a logical sequence of investigations leading to formal conclusions, or rules and principles followed by systematic practice, we let children build familiarity by use. Thus, we give the child a direct-reading balance, and a U-tube pressure gauge, and let him use them and find what they do, before explaining how they work.

We apply this approach to ideas as well as apparatus. In the past, many a child has owned and used a good conception of the conservation of mass without any question being raised or definition being given, or investigation being demonstrated. In fact, both children and physicists make their early steps by letting conservation of mass be taken for granted. Here, we shall let the idea of atoms and molecules be taken for granted at first. In that way we can give children a helpful feeling of progress – 'nothing succeeds like success' – if we let them start with a naïve acceptance of the existence of atoms, which some of them regard as common knowledge.

Of course, if we left all knowledge of science in that naïvely accepted state we should do science, and our pupils, a serious disservice. That would build up a picture of science-by-authority which would spoil our hopes and might even turn into the nonsense of the medieval Aristotelians. However, an informal beginning can establish a working acquaintance which can be given full support later. That would be bad teaching for adult would-be logicians, but it can be good teaching for young would-be scientists. That is how a very young child learns a language, listening to a word again and again, using it with growing familiarity. Semantics and dictionary-work can come later, and critical use later still – neither Shakespeare nor Dr Johnson suffered by the illogic of their first prattling. So we shall begin with some words and concepts taken for granted while children gain acquaintance. Logical and experimental justification will come later.

Note that this analogy comparing the learning of scientific concepts with the learning of language is only intended to illustrate the kind of approach we have in mind. It does not imply that learning the nature of the atoms is down at the level of a baby's learning of the meaning of a word. Nevertheless, when a young child comes to learn abstract words, he first learns the word by copying and unskilled use and then develops an appreciation of the concept for which it is merely a name. We suggest our pupils may learn about atoms in a more mature version of the young child's growing knowledge of abstract concepts. Yet atoms are neither so abstract nor so simple; so we must proceed in this approach very carefully.

In the first Year we shall talk of atoms as the smallest bits of stuff. We ask gently: 'How small?' and give no answer – nor at this stage make any suggestion of how to approach an answer. We let the question nag, as it will in even the young mind. Presently we shall say: 'Atoms and molecules are in constant motion'; but since that is not a commonsense idea, we must at once give some justification from real life: the Brownian motion – *not* just talked about, or illustrated by a large model, or by films, which seem remote – but the real thing, seen with a microscope. That means each child must already have used the microscope for something more familiar. It is one of the many instruments we should help children to use and understand in physics class. That is why we shall suggest letting children use a magnifying glass and a microscope early in their exploration 'concerning the nature of things'. We let notebook records be short and simple; and we do not – yet – burden the story with accuracy or long arithmetic.

These first two Years will prove to be rich ones but full ones to cover in the time available. We must avoid trying to do too much and crowding in material or hurrying children's own experimenting. These are intended to be Years in which children continue to make acquaintance with Nature, and that acquaintance will not be a valuable and lasting one unless the children have time to build it seriously.

Yet most of the topics of the programme, both facts and ideas, will be needed in later Years – classes entering the Nuffield programme at a later Year have to make considerable excursions back into the material of earlier Years for necessary preparation. So, while we urge teachers not to spoil the course by hurrying, we hope they will be able to cover all the main topics. It may be necessary to neglect some side issues, except with a very fast group.

Even at this early stage we must begin to do justice to science as a culture that involves reasoning and imagination. Scientists think: they do not only do experiments, but argue critically about their experiments, and make imaginative guesses and use them. Children should do the same – at their own level – as they learn science. One of the strongest ways of fostering understanding is by asking suitable questions for homework and class discussion; questions that pose interesting problems or call for imaginative thinking. Such questions will help pupils to proceed to the next stage of thinking and doing, and will give them a sense of advancing knowledge – we may even say, 'You could not have answered that a month ago.'

In looking forward we should think of the pupil who learns a piece of physics thoroughly, trying his own experiments and watching demonstrations, discussing with the teacher, doing his own thinking. He makes simple knowledge his own, and says: *'I understand this.'* That is a proud possession, giving a sense of power, a sense of strong knowledge which can be of lasting value in his education.

When we seek lasting values, we cannot expect success with every pupil at every turn. In teaching a language, efficient instruction in grammar and spelling can produce widespread success; but attempts to give an appreciation of the literature will only catch a few pupils' fancy this week and inspire one to two more another week; and a wise teacher considers that a great measure of success. In our teaching of physics for understanding, we must welcome success on the latter scale. But we hope that, as the years go on, all pupils will have a growing knowledge which makes them say: 'Physics is delightful, interesting, powerful; it is great thinking and clever doing. Science makes sense.'

Note to teachers

Please see the *General Introduction* for important notes on:

'The teaching of Energy in this programme' (p. 22);

'The remarkable role of the word "constant" in science' (p. 46).

YEAR 1

CHAPTER 1
Materials and Molecules

About solids, liquids, gases; about crystals, how they grow, how they dissolve; about ways in which we measure

We start with samples of materials on view – brass, glass, lead, sand, nylon, water, air – and ask children to compare them; we offer a closer look with magnifying glass and microscope, giving essential practice with these important tools.

Crystals among the samples may start a discussion that will lead to talk of atoms arranged in regular array.

We provide direct-reading balances and centimetre rules and suggest weighing and measuring rectangular samples, which have whole-number dimensions so that the work goes quickly.

Since some of the samples are of different size, the idea of density may well arise. Liquids, too, are tried and this leads to the question of weighing air, an exciting business to carry out.

1 Class Experiment
Exhibition of materials

Start the year by letting pupils look at a variety of materials: looking, feeling, smelling, weighing them by hand, and so on. These are to be looked at and handled for acquaintance, not for note-taking or classification by systematic scientific discussion. Science is rooted in observation, so our physics course may well start with a gathering together and extension of children's experience. We can raise questions from these observations, which may direct the work in various ways.

A wide variety of specimens of natural and man-made materials should be available to the children. We should have an exhibition of many samples, such as a long shelf with blocks of metal, rocks, samples of crystals, large and small, and some bottles of liquid, etc. These exhibits should stay there on a bench or window-sill or in a corridor and be available to help children become acquainted with unfamiliar materials and to look again at the familiar ones. Children should be free to look closely at them and touch them as much as they like. To begin with all should be labelled; later on some of the labels may be removed.

There should also be specimens of certain materials in sufficient quantity for children to handle them in a lesson. When children are given these, they should be encouraged to feel them, handle them, smell them.

And a few balances and centimetre rulers, and perhaps measuring vessels, strategically placed, may suggest experiments. Balances are likely to be fairly popular; but few will use the rulers. Measuring lengths seems to be a rather artificial scientific activity at this age; and the idea of measuring lengths to calculate an area or a volume does not occur to these pupils because the *need* for those results is not obvious. So we should not press the use of instruments.

APPARATUS *item no.*

Here is a list of suggestions for materials, with those suggested for class use in italics:

(i) Items included in the materials kit *(item 1)*:
blocks of iron, aluminium, brass, lead, soft wood, hard wood, paraffin wax, foamed polystyrene, Perspex, glass, slate, marble.

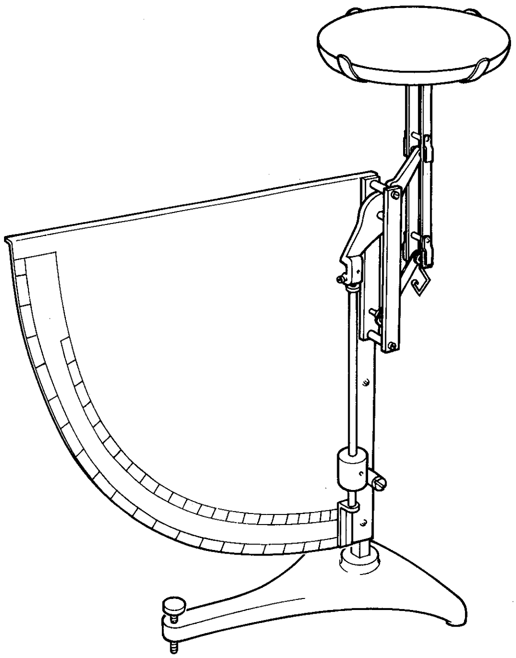
(ii) Items included in the elastic materials kit *(item 2)*:
Rubber, latex foam block, steel spring, bare copper wire.

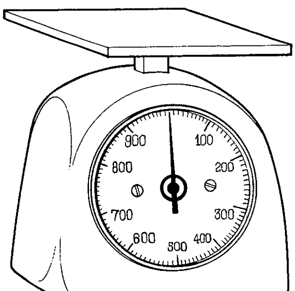
(iii) Items included in the crystals kit *(item 3)*:
alum, *hypo*, *common salt*, washing soda, copper sulphate, calcite, cast bismuth.

(iv) Other items:

(a) Rocks, igneous – granite, basalt; sedimentary – sandstone, *limestone*; metamorphic – *marble*, *slate*, schist.
(b) Various crystals – large and small, some coloured (e.g. *white coffee-sugar*, chrome alum, mica).
(c) Various powders – crystalline and 'formless' (e.g. flowers of sulphur, flour).
(d) Textiles – silk, cotton, wool, nylon.
(e) Substances with smells – bleach, camphor, naphthalene, curry powder, a block of kitchen soap.
(f) Household materials – vinegar, olive oil, gelatin, starch, chalk, plaster of Paris.
(g) Man-made materials – plywood, block board, concrete, ceramic, greaseproof paper, Formica, polythene sheet, a tungsten carbide drill.
(h) Food – wheat, maize, barley, peas, beans.
(i) Liquids in bottles – water, glycerine, oil, alcohol, olive oil, mercury, bottle of pitch (or a cardboard box with pitch in it and a hole for the pitch to ooze out slowly), bottle containing ice and water.
(j) Gases – bottles labelled 'air', 'vacuum', 'CO_2', 'ammonia'; gases in balloons – air, natural or town gas, carbon dioxide, hydrogen. (These bottles and balloons will need to be prepared beforehand – see below.)

(*v*) Additional apparatus: some of the following should be available near the exhibition for the use of those children who wish.
Several lever-arm or simple top-pan balances *42*
Hand lenses *24*
Plastic measuring rules *25*
The balances should *not* be equal-arm or chemical balances. Either lever-arm or top-pan spring balances are suitable.





Instructions for filling balloons

APPARATUS *item no.*

3 Small balloons, preferably of different colours
1 Aspirator (10-litre) *523*
2 Rubber bungs fitted with glass tubes
1 CO_2 cylinder *19/1*
Rubber tubing for connection to water tap

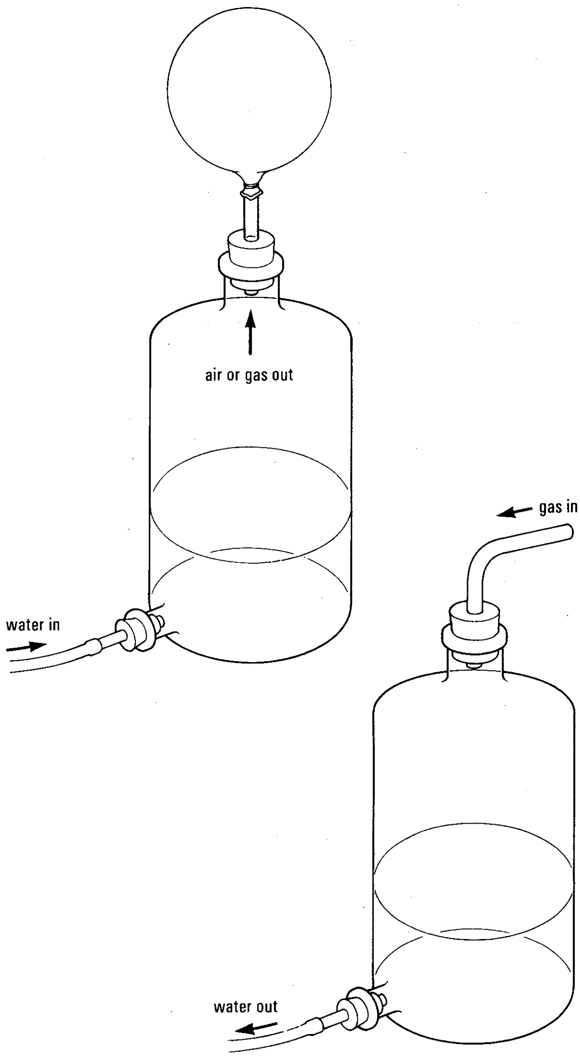
NOTES

1. The balloons should be filled immediately before display. Hydrogen in particular will diffuse quite quickly through the rubber of the balloon.
2. It is helpful to work a balloon first before inflating it. This is done by blowing some air into it and stretching the material between the fingers so that all parts of the balloon are equally stretched. This softens the rubber and ensures that the balloon blows up symmetrically.

PROCEDURE

1. Air

Connect the balloon to the top of the aspirator. Fill the aspirator with water by connecting the lower end to the water tap. The water displaces the air which fills the balloon. When the balloon is full, remove it without letting the air out and tie a tight knot in the rubber neck.



2. Carbon dioxide, natural or town gas, or hydrogen
The procedure for filling the balloon is the same as for air, but first the aspirator must be filled with carbon dioxide, or with the gas or hydrogen.

The aspirator is first filled with water and the top is connected to the appropriate gas supply (carbon dioxide from the CO_2 cylinder, natural or town gas from the gas supply, hydrogen from the special apparatus borrowed from the chemistry department). The water is drained out whilst letting the gas in at the top. Then quickly fit the balloon to the top of the aspirator in place of the gas supply. Connect the side tube to the water supply and gently force the gas out into the balloon.

Hydrogen is lighter than air and should be used in preference to town gas.

PROCEDURE

Children should walk along the exhibition row and look at the samples and feel them and handle them, and smell them if they like.

In discussion, with the duplicate samples in hand, children and the teacher might make some classifications; but that should be done gaily, and a wide variety of different ideas encouraged without any precise definition, e.g.: bright and dull before the more precise metal and non-metal, hard and soft, 'light' and 'heavy', clear and opaque, solid and fluid, solid, liquid and gas, regular shape and irregular shape, etc.

In some classes a game of 'Twenty Questions' can be developed which will make classifying very popular. The exhibition should stay there for several weeks‡ and children can always go back and they can always ask.

Vacuum? If children do not ask what to do about the vacuum bottle, the teacher will have to open it under water anyway. But if the children do not ask how the vacuum got there, the pump that the teacher used beforehand should remain hidden!

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‡ In many laboratories that are used by several classes there are considerable difficulties in leaving the exhibition out on a window-sill or table for some time. But other classes may well profit from finding it there and are likely to respect it sufficiently. If the exhibition *cannot* be left out, pupils should be told they can always ask for its specimens and look at them again.

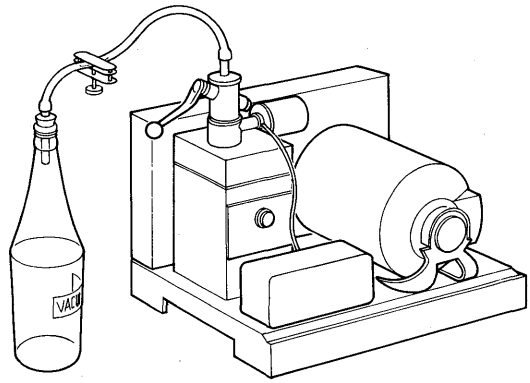
Investigation of an evacuated bottle labelled 'vacuum' *(Optional now)*

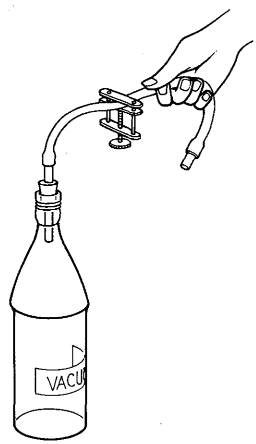
APPARATUS *item no.*

1 Motor-driven rotary vacuum pump *13*
About 1 m of pressure tubing to fit the tube on the bottle *10DD*
1 Large transparent trough *532*
The bottle must have a well-fitting rubber stopper in the top with a glass tube through it to which is attached a short rubber tube with a screw clip. An ordinary bottle, such as a lemon squash one, should be used and not a special 'laboratory' flask.

PREPARATION

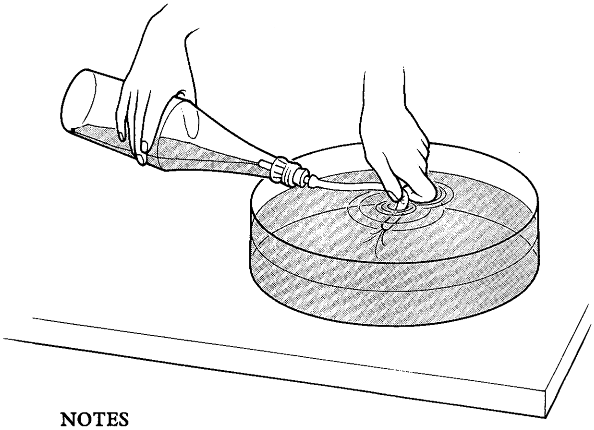
The rubber tube is connected to the vacuum pump and the air inside the bottle is removed. The bung and glass tube must be tight fitting. When the air is removed, the clip on the rubber tubing is closed. It may help to keep the vacuum if a glass rod is inserted in the end of the tubing.





PROCEDURE

The bottle labelled 'vacuum' should be put with the other exhibits and it is hoped the children will ask about it. When this is discussed, the teacher shows there is nothing in the bottle by immersing the neck of the bottle in water and removing the clip. Water will rush in to fill the space. If the vacuum was a good one there should be little or no air inside the bottle. If the pump was not very effective or if there was a leak, then the water will not completely fill the bottle and some air will be seen in it. There will always be a small bubble left, however well the bottle is evacuated, due to air that was dissolved in the water.



NOTES

1. Reject any old or perished rubber bungs or tubes for this experiment, as they develop cracks and will not hold the vacuum.
2. It is essential to use rubber pressure tubing for connection to the pump otherwise it is liable to collapse (plastic tubing is not advised). A long tail of pressure tubing would be inconvenient when the bottle is opened under water; on the other hand there should be plenty of pressure tubing, about 1 m, between the bottle and the pump to make the work easier. The best arrangement is to have two pieces of glass tubing: the first, in the outlet to the bottle, is connected by a short piece of rubber tubing with the clip attached to the second (which is replaced afterwards by a rod as a stopper) and this second piece of glass tube takes the long length of pressure tubing, in turn connected to the pump. The short piece of tubing can be of medium-wall rubber instead of pressure tubing if it is short and the glass tubes are pushed into it close together to hold it open.
3. It is advisable to use coloured water when opening the bottle.

Note-taking? There is no need for making notes here: that would only slow down children's gaining of experience and turn a light-hearted discovery process into a heavy-footed directed procedure. That is true of much of this year's work.

Often, in teaching, we find children asking to take notes, wanting to take notes. Sometimes this is a simple wish stemming from interest in learning about Nature, the 'collector's passion'. In that case we should give note-taking our blessing, but should not encourage it into occupying much time at school (or at home) or we may find it becoming the master instead of the servant of genuine experiment.

In many cases however, we wonder whether the children's requests for notes come from habit in other classes (in subjects that do not have our good fortune of laboratories for experiments) or from anxiety about marks and examinations. In such cases, we must not stop note-taking but we should lessen its importance by repeated reassurances. We need to say, in suitable vocabulary, 'The experiment is the thing. You may be asked in exams about the things you really did; but you will *not* be asked to write down things that you have learnt from your notebook.'

A wise teacher may even wonder whether some of the feeling in the class that note-taking is important comes from his own habit and training. If we reflect on our own training, we most of us find that while we learnt good habits of note-taking as part of our scientific work – an essential part of research work – it did bulk large enough in early stages to take more than its proper share of attention. If we look at the records of research scientists, we find them complete but informal. With this in mind, teachers are likely to lighten their insistence on formal notes.

Tests? We should no more prepare or give an examination on classifications and names than a sensible restaurant sets its customers an examination, just as they are going out, on what was on the menu.

PROGRESS AND OTHER QUESTIONS FOR TEACHING

The *Pupils' Text* provides sets of 'Progress questions' and of 'Questions' at frequent intervals throughout. The set which follows directly on the Exhibition of Materials states: 'Most of these progress questions should be answered in the laboratory with the experiment in front of you. In many cases the questions will help you to see the point of an experiment.' In one respect such questions may act as a worksheet. Speaking generally, the sets of questions require rather more thought than do the progress questions.

In our suggested teaching programme, problems that lead pupils on in their thinking – or ask them to criticize or review what they have done – play an essential part. Our problems are not intended to be routine work to fill in time. They are intended to do essential teaching.

There are many more problems than a class will have time to use in the course of a year. Teachers will need to make a careful selection. Too many problems will only give a sense of rush or else dull pupils' interest. On the other hand, too few problems will leave the teaching without that essential help towards critical constructive thinking that we hope our questions and problems will give.

As well as their major function in teaching, the questions will help to warn pupils – and teachers who are new to the programme – of the kind of question likely to be asked in examinations.

LOOKING AT SMALL THINGS: MAGNIFYING GLASS & MICROSCOPE

Each child should have a magnifying glass and then access to a microscope in turn. (There must be *one hand lens for each child*; if not, we must send for more – we would not expect children to share a soup-spoon, one for every two.) Explain that the lenses cost money, and are needed for use in the laboratory again and again so they are not souvenirs. Yet if pupils want to take magnifying glasses home to look at things, we hope that teachers will allow them to borrow them. Something taken home with permission almost always comes back safely. We hope that teachers will sometimes even allow a microscope to go home for an evening or a weekend. That can establish a very important link with parents. Our programme is strange to many a parent who has doubts or questions which are best answered by seeing at first hand what we are doing. An experiment taken home is a good ambassador.‡

Microscopes: a note to teachers Microscopes raise a much more difficult problem. Looking at things with a microscope is thrilling, a great delight if one can make one's own choice of things to look at, but only if there is sufficient time. With this unfamiliar instrument, young children need much longer than we would expect. To make this work with microscopes successful we should allow at least a double period and perhaps three or four periods with those instruments.

These will not be periods of easy teaching: children will need encouragement and help. However, teachers should not feel that it is necessary to run from one pupil needing help to the next, because pupils who wait will find their own way out of some difficulties. This is, in fact, the beginning of a very important piece of education in science laboratories: children must begin to learn to meet their own difficulties. Encouragement rather than detailed help is what is needed.

Teachers who are familiar with the problems of showing things with a microscope to young pupils, and are skilful at arranging for pupils to take turns, will be tempted to carry this out with a few microscopes, say only one or two – organizing the class with other work so that there is only a short queue for each microscope. That would be excellent if our aim were to let each child *see* one particular thing, as in looking at a lantern slide picture. But here our aim is entirely different: it is to give young pupils a new instrument that enables them to enlarge their acquaintance with Nature in a powerful and thrilling way. We want them to feel the importance of this instrument to scientists and to know that they can use it confidently themselves, as young scientists. That can only be done if they use microscopes themselves and have the use of the instrument for a considerable fraction of the class time. With that will come the strong sense of delight in exploring Nature that goes much deeper than the temporary pleasure of just being shown Nature in a demonstration.

‡ To encourage home trials by pupils as an important educational experiment a small private fund is available to underwrite the possible loss of magnifying glasses, microscopes, smoke cells, possibly the complete equipment for oil film. In later years we hope even magnets will be taken home – despite their reputation for disappearing – because they are essential for simple home experiments with electric motors, etc. Where a school lends such items of apparatus to a pupil to take home for experiments and finds that they cannot get them back or the apparatus comes back damaged or broken, they should apply to:

The J. Willmer Home Experiments Endowment
C/o A.S.E.
College Lane,
Hatfield, Herts

The General Secretary, administering this fund, will only ask whether the apparatus went on loan with permission, whether the Class is following a complete year of our Nuffield Physics programme, what was damaged, and how much the cost. He will not want to know the name of the pupil and he will not want the usual formal details of a report of damage. The cost will be reimbursed most happily.

Thus, one microscope for every four pupils is a *minimum*. We wish it could be one microscope for every two.

The Biology section of the Nuffield Science Teaching Project hopes there will be one microscope for every four or, at the most, six pupils. In many schools the authorities in the biology department feel doubtful about lending their microscopes for use by these young pupils in a different laboratory. We consider that this work with microscopes is so important (both now and to see Brownian motion) that unless there is a clear arrangement by which the biology department *will* lend microscopes (for a week now, and another week later in this year), microscopes must be bought, one for every four pupils, as part of the physics equipment.

We believe from experience in trials that schools will not regret this expenditure. These need not be expensive microscopes used for advanced biology – there are now simpler instruments which cost much less.

However, the aperture of the objective lens must be fairly large – to let in enough light for easy use – though the power need *not* be high. Small toys or 'field microscopes', used for prospecting or biological collecting, are unsuitable because their aperture is too small.

Furthermore, microscopes will be needed again later this year, for pupils to look at the Brownian motion of smoke in air. We regard that as a vital experiment in support of the teaching of this year, something that we believe each pupil needs to see for himself by looking at it directly through a microscope and not just by looking at a film or another demonstration. However, the Brownian motion is even more new and strange than the things pupils will look at now with their microscope; and what one sees is complicated by poor illumination and convection. So it is essential for pupils to come to that later experiment already familiar with microscopes and confident that they can use them well. If this involves the school authorities in considerable cost or trouble in buying or borrowing microscopes, and if the children's own work with microscopes takes up several periods without at the time seeming immediately productive, we give strong assurance that all this will prove worth while.

1a Class Experiment
A closer look

APPARATUS *item no.*
36 Hand lenses *24*
8 Microscopes *23*
8 Illuminants *47*
8 Transformers *27*

PROCEDURE

Pupils should look at anything they want to, first with a magnifying glass and then with a microscope: sand, salt, blotting paper, talcum powder, a hair, their own handwriting, blood, and then red ink, a fingerprint, a postage stamp, salt dissolving, some rocks such as granite. (The teacher should suggest only a few of these, and leave children to enjoying finding others.)

THINGS THAT SHOW ORDERLY ARRANGEMENT

Crystals

Children should handle crystals themselves, as well as just look at them in the exhibition. If some large specimen crystals of alum, sugar, etc., are available, these should be handed round now. But, more important, each child should have some small crystals to examine for himself. These need not be large exhibition specimens, but they should not be so small that a magnifying glass is required to see them.

2 Class Experiment
Looking at crystals

APPARATUS *item no.*
Large alum crystal *3C*
Calcite crystals *3A*
Hypo *3K*
Castor sugar
Sugar crystals (type used in coffee)
36 Hand lenses *24*

PROCEDURE

We suggest giving each child several crystals of photographic hypo; and several crystals of white 'coffee sugar'. Neither is harmful so children may keep them. (Hypo comes in a coarse form when bought in bulk; and the little white slabs sold as 'coffee crystals' are, the manufacturers assure us, genuine crystals, though they may be somewhat abraded.) Pupils should be encouraged to look for other crystals at home. They should also be encouraged to look at their crystals with a hand lens to see if they can find more details.

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3 Class Experiment
Watching crystals grow quickly

APPARATUS *item no.*

40 Small test-tubes *546*
1 Bottle of hypo crystals *3K*

The quantity allows one test-tube per pupil with some spares. Any small tubes will do, but the wider they are the more hypo is needed.

PREPARATION

Some hours before the class, preferably the day before, put a few cm^3 of photographic hypo crystals in each test-tube (to a depth of 4–5 cm) and melt them by gentle warming. The crystals will melt in their own water of crystallization. If they do not do that easily, add a drop of water to the stock of crystals so that they are damp.

Allow the tubes of melted hypo to cool down to room temperature. If the tubes are left a long time after cooling, the hypo may recrystallize in some. A few spares should therefore be prepared.

The recrystallization might be started by dust, so it is advisable to cover the mouths of the tubes with a sheet of paper until they are taken to the class. It is advisable to avoid jarring the tubes as that may start recrystallization.

PROCEDURE

Each pupil should be given a test-tube with the cool liquid hypo in it. Ask him to drop one crystal of hypo into the liquid and watch very carefully.

NOTE

Do not suggest looking for the rise of temperature on crystallization. Some pupils will feel it, but others who miss it can meet it at a later stage.

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4 Class Experiment
Growing crystals of alum or copper sulphate

APPARATUS *item no.*

32 Small jars
32 Beakers (400 cm^3) *512/2*
Alum or copper sulphate *3J, 3N*
1 Bucket (plastic with lid) *533*

There should be one jar for each pupil. Jam-jars are quite suitable.

PROCEDURE

1. The saturated solution

Prepare a solution of the salt which is saturated at room temperature. This is best achieved by allowing a super-saturated solution to deposit its excess solid, as explained below.

To prepare the working solution, dissolve the salt in warm water (about 50 °C) at a rate of 40 g per 100 cm^3 for copper sulphate and 30 g per 100 cm^3 for potassium alum. Seven litres is sufficient for a class of thirty-two using jam-jars. Pour this solution into the bucket, close the lid, and allow it to cool to room temperature. This solution is now super-saturated.

Seed this solution with a pinch of tiny crystals and leave it in the closed vessel for two or three days, shaking occasionally, to become saturated at room temperature. Pour off the clear saturated solution into another glass vessel and close this with a lid.

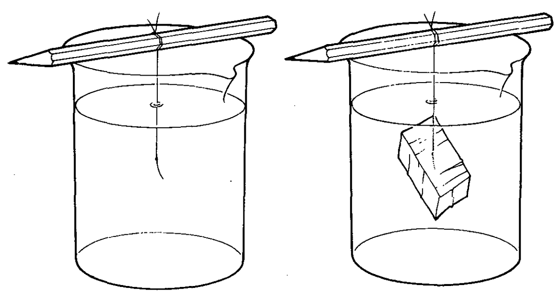
2. Seed crystals

One method of producing the seed crystals is to dip a length of thread into the saturated solution and then to hang it up to dry. Small crystals will appear on it and the whole thread is then hung in the solution. After one or two days examine the crystals which have developed and break off all but the best. These then form the seeds for the next stage.

Another method is to place about 50 cm^3 of the prepared solution in an open beaker and to allow it to evaporate overnight. The seeds resulting are sorted and dried, those which are perfect in shape and about 3 mm long being retained.

3. Growing the crystals

Where the first method for seeding is used, the thread with its perfect seed crystal is suspended from, say, a pencil laid across the top of the jar. The jar is filled with the saturated solution until the seed is completely covered. The jar should then be covered with a piece of thin cotton cloth



(for example, muslin or cheese cloth) which is held in place with an elastic band. It is then left undisturbed and at an even temperature for several days.

Where the second method is used to obtain seed crystals, it will be necessary to tie the seeds to a short length of cotton or thread. This is not an easy process and children should be advised to prepare a slip knot and to slip this over the seed rather than to use a reef knot or granny knot. Once the crystal is secured to the cotton, proceed as above.

NOTES

1. In a school with many streams, each pupil should still be provided with a jar in which to grow his own crystals. However, this poses a tremendous problem of storage. Such a school would be wise to consider replacing the jars by tapered glass tumblers that can be stacked. The supply of material for crystals must of course be provided in large quantities; but the beaker for seed crystals can be made to serve several pupils or several classes.
2. For experiments at home, pupils may be encouraged to try growing crystals of such common substances as sugar and soda, but they should also be provided with plenty of alum to take home to try.
3. If the room temperature rises suddenly, the solubility (of most salts) increases and we lose the necessary saturated solution. This is the reason for the need for an even temperature, day and night.

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5 Home Experiment
Growing crystals

The *Pupils' Text* suggests that pupils might like to grow some crystals of such common substances as salt, sugar, or even Epsom salts at home using a jam-jar or even an egg-cup as the vessel. The experimental details are as given above in Experiment 4.

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6 Class Experiment
Watching a crystal grow under a microscope

APPARATUS *item no.*

8 Microscopes *23*
8 Illuminants *47*
8 Transformers *27*
32 Microscope slides *3G*
8 Bunsen burners *508*
8 Beakers (400 cm^3) *512/2*
8 Pins
1 Bottle common salt *3L*

The number of pupils that can do this experiment at once depends on the number of microscopes. The minimum number is one for every four pupils.

PROCEDURE

Prepare an almost saturated solution of common salt overnight and decant this into the eight beakers. Warm a microscope slide over a low Bunsen flame and place a drop of salt solution on it so that it may be observed under a microscope.

In the end the microscope will have to focus on a plane just above the surface of the slide so as to see the first layer of crystal forming. It may be convenient to focus on to some mark on a piece of paper placed under the objective in order to find the correct position.

We recommend giving children salt rather than materials such as salol, which forms crystals more easily, because salt is a common substance children already know. At this early stage of doing science, we hope children will deal first with material which they already know at home. Salt has the peculiarity that its solubility does not change appreciably with temperature. Therefore we cannot produce crystals by making a hot saturated solution and then just letting it cool down. Instead we must compel crystals to form by letting some of the water of our salt solution evaporate. So the microscope slide itself must be hot, and the solution should be warm or hot, so that evaporation into the air is copious. Heating the slide in hot water will not suffice – or, rather, crystal-forming will be slow. It is better to warm the slide over a small Bunsen flame. We suggest that there should be several small Bunsen burners running for communal use. As in so much experimenting – ranging all the way from a young child's first experiments to a professional researcher's work – much is gained by a first rough try to see if the process will succeed. Once children have made salt crystals and looked at them, they become mysteriously skilful in making more. The brine should be a concentrated, practically saturated solution, available in a beaker from which children can take a drop at a time.

NOTES

1. Again, no note-taking is necessary. A child who really wants to sketch what he sees may do so, of course. Unless he is genuinely keen, we should encourage a child who asks about taking notes to hurry on and enjoy seeing things.
2. The outcome of this experiment should be 'I have seen things with a microscope', or even 'I can make a microscope work.' Though untrue, that is an unusual and refreshing boast.
3. These are familiar activities and instruments for us. But to children they are new and strange and deserve plenty of time. If playing with magnifying glasses and microscopes extends beyond two periods let it continue next time with an easy heart. It will be clear when this work is becoming casual messing about, and then children can move on to the next, entirely different, experiment while others are still working with microscopes.

INTRODUCING THE IDEA OF ATOMS THROUGH CRYSTALS

Both teacher and children should ask questions about crystals, and we should encourage the suggestion that some things must be arranged in a regular array inside crystals, things too small to see – 'atoms'. Otherwise, it is difficult to see why crystals make such regular shapes, and how 'they know how to make the same shape every time'. (Of course professional crystallographers will warn us that the same material makes a great variety of shapes, as judged by the layman, although they are to him all of the same fundamental pattern. To children, at this first careful look at crystals, the idea of some standard shape is likely to seem quite clear.)

'Atoms?' Children will certainly have heard the word 'atoms' but only some will know what it means. Though the word may be used easily, most have not reached the state of *wondering* about things that are far too small to see. So we need to introduce the idea gently, as a strange one that does not seem necessary and may not even seem particularly interesting yet.

When we have given children the idea of small particles or bits of which everything is composed, we are likely to find that they soon take atoms for granted – and so also may we, at this stage. But already we can ask the question 'How big are atoms?' However, we should leave that question unanswered – with a promise, if necessary, of some answer later this year.

Molecules The word 'molecule' may be entirely strange; and when we try to explain what molecules are, they are likely to seem mysterious. If children take molecules and atoms as much the same, we shall do little harm and we shall avoid an unhelpful sense of mystery. Chemistry will clarify the issue at the right point.

Some teachers find that wallpaper gives a good illustration of a pattern of 'atoms' within a larger pattern of 'molecules' within the whole covering of the wall representing the whole crystal.

7 Class Experiment

Building a model crystal with marbles

Now that children have grown some crystals and have met the suggestion that crystals may be made of some tiny 'atoms' arranged in some regular way, they should try building their own crystal model. It is best if they can use common materials that are easily obtainable so that each can make his own model and even perhaps continue at home. Marbles from a toy shop are of a convenient size for 'atoms' in the class experiment models. Those marbles are not all of uniform size but we find on experiment that they are uniform enough for pupils to be able to pile them in an array, using a little care. (Trials with smaller glass balls, from chemical suppliers, have led to troubles with balls getting spilled and lost; and those small balls have not proved easy for children to work with.)

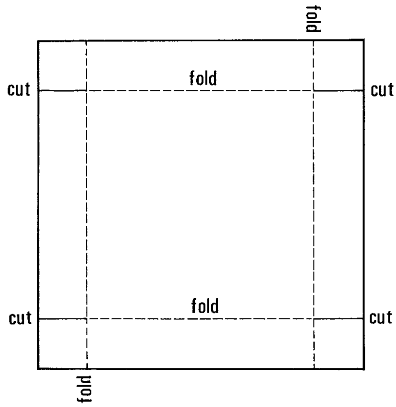
APPARATUS *item no.*

Supply of marbles (about 1.5 cm dia.) *12B*
16 Pieces of thin card (about 12 cm square)
The two-dimensional kinetic model kit (item 12) contains 800 marbles and these should be used for this experiment.

PROCEDURE

The trays in which the marbles are to be stacked are improvised from the sheets of card. These are marked out with lines about 2 cm from the edges, cut as shown in the diagram, and the edges folded up and stapled to form a square tray.

The tray will hold a layer of twenty-five marbles. On this can be built up layers of sixteen, nine, four, and one marbles to form a pyramid.



8 Demonstration
Large crystal models

APPARATUS *item no.*

1 Wooden base with ridges *3E*
55 Foamed polystyrene spheres (37 mm diameter) *3B*
1 Large alum crystal *3J*

PREPARATION

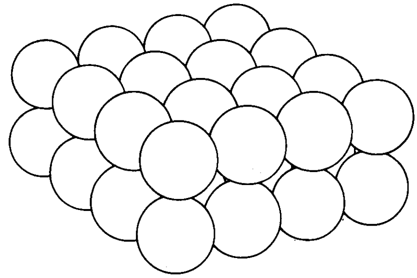
Models (1) and (2) below are necessary, model (3) is optional.

The teacher should prepare the models some time before the lesson by joining spheres together with a suitable adhesive. Conventional 'glues' will probably not work, but a good adhesive is made by dissolving some sheet foamed polystyrene (or one of the spheres) in acetone (or, better, in some amyl acetate). The adhesive should be very thick in consistency and should be applied with a wood splint to the spheres at the points of contact. Then the spheres are pressed firmly together. They should be left twenty-four hours to harden.

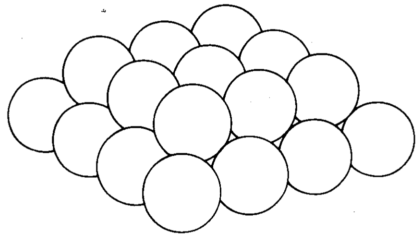
Some may prefer to join the spheres together using cocktail sticks or double-ended screws. In practice, glueing is easier.

1. Simple cubic lattice
Four layers should be made and then placed one on top of the other. The layers can be fixed permanently together, left separate, or tied together with cotton.

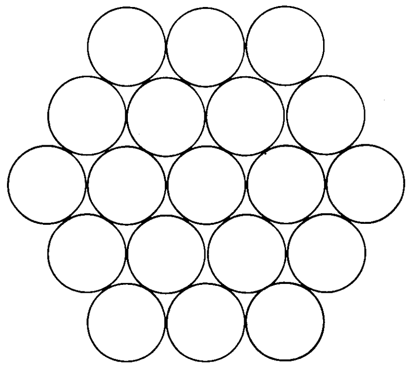
2. Body-centred cubic lattice
a. This can be built up as illustrated by putting a second layer of nine spheres on top of the first layer of sixteen in the position indicated. On top of this layer is then put a layer of sixteen (already stuck together) similar to the first, and the process is repeated.
b. Alternatively, build a pyramid, starting with a 4 × 4 base, then nine spheres in the second layer, four in the third, and one in the last.
c. Or make a large number of 4 × 4 layers and assemble crystals, both simple cubic and body-centred cubic, by moving the layers on each other.



Simple cubic



Body-centred cubic



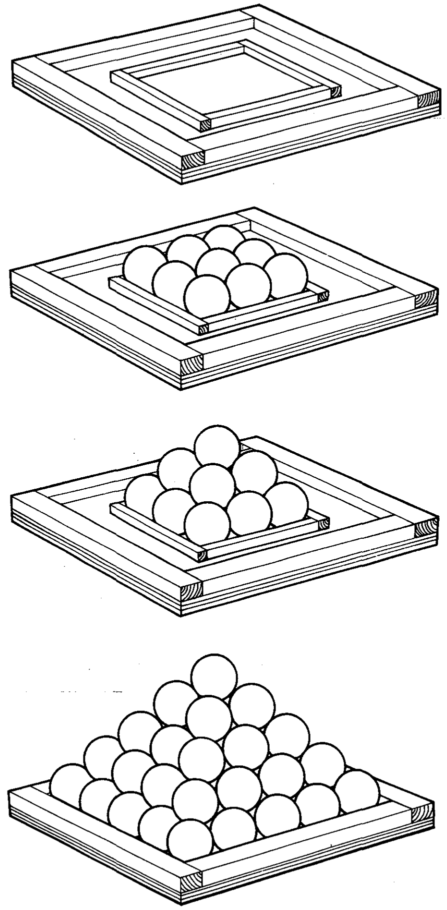
Hexagonal close-packed

3. Hexagonal close-packed lattice (Optional extra)
A close-packed single layer structure can be built, as shown, with each sphere touching six others. A second layer similarly constructed, placed on top of the first, is displaced slightly so that the spheres of the second layer fit into depressions in the first. Further layers can then be placed on top.

PROCEDURE

Form a square with three balls in each side, using nine balls in all, on the special wooden base board. Then put four balls on this base and one on the top to form a pyramid.

Now let the crystal 'grow' by the addition of more balls one at a time. Add balls carefully until there is a pyramid with a 4 × 4 base.



Then add more balls to make a 5 × 5 base.

The teacher can use his model to give considerable help to pupils who need it and to carry the discussion further. However, the most valuable contribution of this teaching is likely to come through pupils' own work in building their models, both because they have a sense of possession and because they learn by modifying arrangements and meeting difficulties.

A large octahedral crystal of alum should be shown and compared with the model.

The teacher should show models of crystals ready-made with large visible balls stuck together, and point out that those models agree with the way in which crystals seem to keep their shapes.

After the crystal models have been produced by the teacher, they should be added to the other exhibits.

Different packings should be shown but no attempt should be made to enlarge on detail. Above all, long names should not be given for different crystalline structures.

It should merely be pointed out that these models appear to agree with the way in which crystals seem to choose and keep their shapes.

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9 Demonstration

Cleaving a crystal

APPARATUS *item no.*

Large calcite crystals for cleavage *3A*

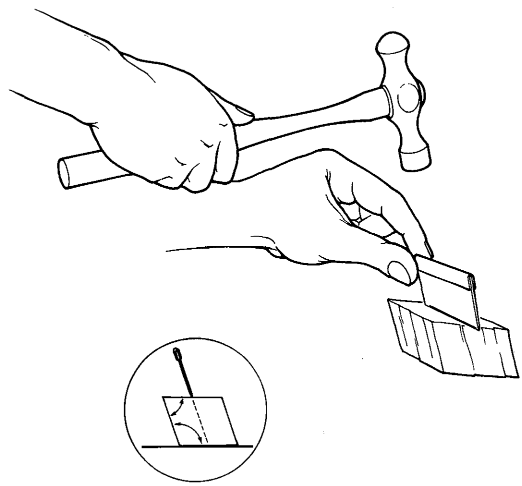
1 Single-edged razor blade *3H*

1 Light hammer

Additional supplies will be necessary as a fresh large calcite crystal will be needed for every class taught.

PROCEDURE

Show the cleavage of a large crystal of calcite, by placing a single-edged razor blade on it with the right orientation and giving the blade a sharp tap with a light hammer.



This is an impressive operation that requires the skill that comes from practice rather than great force. Teachers will find that a little practice soon gives them skill in the art of cleaving crystals. The PSCC Film on 'Crystals' shows the technique, in the hands of a master. Holden and Singer's book *Crystals and Crystal Growing*, published by Heinemann (1961) in the Science Study series, also describes it. This excellent paperback gives details, practical description and some theoretical description intended for older pupils.

(The alternative method, sometimes suggested by beginners, of using a screwdriver or a carpenter's chisel, with much greater force, is not a proper way of cleaving crystals. That is breaking up a crystal by brute force and misses the whole beauty of the art – and fails to teach the essential point of easy, neat cleavage. We hope that, however tempting that 'brute force' method may be, teachers will avoid it.)

This is a surprising and important demonstration. It is practically meaningless to all pupils except those in the front row unless a large crystal is used. Therefore *the large calcite crystal must be regarded as expendable material* – like acids in chemistry – and a new crystal obtained for every class that is taught. If it weighs only a few grams it is far too small.

Molecules moving in among each other

10 Class Experiment
Dissolving crystals

APPARATUS *item no.*
Common salt *3L*
Beakers (400 cm^3) of water *512/2*

PROCEDURE

Each pupil should dissolve some salt in water in a small beaker and watch it. We ask what has happened to the crystals. To an adult scientist this seems so trivial an experiment that one would not expect to take the trouble to do it; but to these young pupils it is drawing attention to something they have not worried about before, and in the hands of a wise teacher it will lead to an interesting discussion.

We may also raise a question about volume changes when salt dissolves in water.

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11 Demonstration
Salt dissolving

APPARATUS *item no.*
1 One-litre volumetric flask *517*
Common salt *3L*

PROCEDURE

When sodium chloride dissolves in water to make a saturated solution, there is a $2\frac{1}{2}$ per cent contraction in volume. One would never notice that in a beaker; and even in an ordinary flask it would be barely perceptible. However, if a volumetric flask is available from the chemical laboratory, the volume change will be visible in the narrow neck. It is essential to remove all air bubbles from the salt that is to be dissolved, therefore it must be thoroughly wetted at the beginning of the demonstration. (The solubility of salt *does not change much with temperature*, so there is little profit in using hot water.) Place 300–400 g of salt, in small crystals (but not in rocks or very fine powder), in a one-litre volumetric flask. Pour in enough water to cover the dry salt, and swirl the water round in the flask to wet the salt and let air bubbles float up the top. This will not be enough water to dissolve more than a little of the salt that has been put in; so pupils will still see a lot of salt crystals there.

As soon as the air bubbles seem to have been removed, fill the flask to the mark with water. Label the water level clearly with a wax pencil or dark tape, point out that most of the salt is still there, as a solid waiting to dissolve, and shake up the flask to hurry the dissolving. When as much salt has dissolved as will, a small contraction will be visible.

None of this work should be laboured – it is intended to convey an atmosphere of excitement, to indicate wide horizons for observation and depth of imaginative thinking.

Continuing with crystals *(Optional)* Many exciting things can be done with crystals, but this is the beginning of a busy year, so further suggestions are not offered here but will be found in Holden's *Crystals and Crystal Growing*.

Some pupils will certainly want to continue with crystals. It is not always the fastest or brightest pupil who will pursue extra studies; sometimes a slow pupil derives great enjoyment – and makes great progress – by pursuing a special interest and becoming a proud expert. In that way, a child who might have stopped at car-number-collecting becomes an adviser on the feeding and care of tropical fish or becomes so skilful with crystal growing or soap films that he can boast a genuine understanding of science. In all our work, we should try to provide opportunities for pupils to widen their interest and sympathies. Not every pupil will pass through each door we open, or even look through each window, but we should never neglect the possibility.

Weighing and measuring solids

Some children may have weighed specimens when they first looked at the exhibition of materials. All will have noticed strong differences and that question can now be pursued (but not with any great emphasis) either before or after the discussion of crystals.

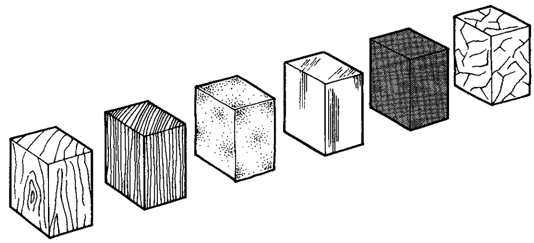
Here there will be some things to record in notebooks. Great precision of weighing is not necessary or even helpful: the aim of this experiment is to look at materials quantitatively, and not to develop great precision – that comes easily at a much later stage. However, a comparison of results all round the class may promote some natural comment on accuracy.

(Teachers should remember that there is a long and strong tradition of beginning physics with careful measurements of volumes and masses, and calculations of densities with considerable care over arithmetic. That is in some ways an admirable occupation for small fingers manipulating instruments; and it affords careful, if extremely boring, 'training' in arithmetic. Yet, however skilful and successful the teaching of it, the outcome seems to be technical skill rather than a sense of understanding physics; and the practice of those careful measurements and calculations takes considerable time. So, in our programme, we are anxious to experiment with teaching that does not emphasize formal work. If we regret losing that, or fear pupils will be hampered later on by lack of it, we should reflect that at a much later age the techniques can be acquired very quickly, and the arithmetic can be carried through with speed and understanding. So those of us who are skilled in careful teaching in this region will need to minimize the usual emphasis.)

12 Class Experiment
Putting materials in order by weight

APPARATUS *item no.*

From materials kit: *1*
Blocks, each 5 × 4 × 3 cm, of:
Soft wood *1A*
Hard wood *1B*
Aluminium *1D*
Iron *1E*
Foamed polystyrene *1F*
Paraffin wax *1C*
And of various other sizes:
Aluminium (5 × 5 × 8 cm) *1N*
Aluminium (2 × 2 × 10 cm) *1J*
Perspex (2 × 2 × 10 cm) *1G*
Slate (2 × 2 × 10 cm) *1I*
Glass (2 × 2 × 10 cm) *1H*
Soft wood (2 × 2 × 10 cm) *1K*
Lead (5 × 5 × 2 cm) *1M*
Brass (2 × 2 × 5 cm) *1Q*
Marble (2 × 2 × 10 cm) *1L*
There should be a complete set of at least the first six blocks (5 × 4 × 3 cm) for every four pupils.
8 Lever-arm or simple top-pan balances *42*



PROCEDURE

Pupils, conveniently working in pairs, are asked to close their eyes and then, by 'hefting' the sets of blocks of the same size, to put them in order by weight. This will establish general knowledge that the same size of chunk of different materials may weigh very differently. Each pupil should make a note of the order in which he placed the set of blocks he used.

The pupils should then weigh each of their blocks and record the weight of each one. Does the order found by 'hefting' agree with the order found by careful weighing?

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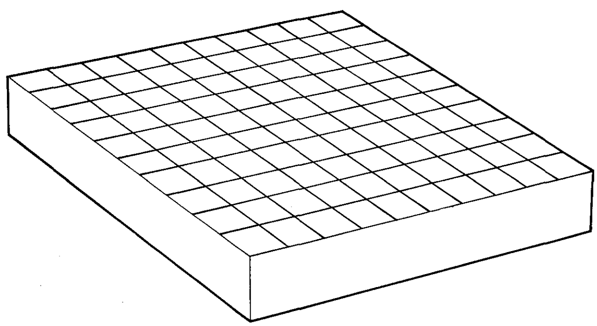
13 Class Experiment
Weighing and measuring solid blocks

APPARATUS *item no.*

As in Experiment 12 above, together with:
16 Plastic measuring rules (graduated in cm) *25*
Foamed polystyrene (5 × 30 × 40 cm) *10*



The plastic rules are marked in centimetres only. It is important to use these in this experiment and not to use more conventional rulers which are also marked in millimetres. If the rules are only marked in centimetres, pupils will measure to the nearest centimetre. If there are millimetres as well, some will measure a width as 1.9 cm and thereby ruin the whole experiment in a mass of complicated arithmetic in a misplaced attempt to achieve 'accuracy'.

There should be sufficient balances so that there is one for every four pupils. These should read up to 1000 g. Chemical balances (or other equal-arm balances) should *not* be used. For some pupils it may help considerably if the second scale on the lever-arm balance is covered over with black masking tape.

The large sheet of foamed polystyrene should be marked to show that it is the equivalent of 10 × 10 or 100 of the smaller polystyrene blocks.

PROCEDURE

Each of eight or so of the blocks is weighed and their sides measured. The results are to be noted down, block by block. The *Pupils' Text* asks whether it would be a good idea to include the weights of all the blocks measured in the table of the weights of the similar-sized blocks used in Experiment 12. The pupils are also to consider the problem of finding the weight of the large polystyrene block. The intention of the work is to raise the question of the 'weight for some standard volume'.

Discussion with teachers: a light approach to density We want pupils to develop a feel for density as a thing we know about a material – a useful qualitative concept rather than a quantitative definition and scheme of measurement. After Experiments 12 and 13 we could lead the teaching on to a discussion of weighing different sizes and working out the weight of some standard size, such as a unit cube, but we find (from our trials with actual classes) that this imposes discouraging barriers and delays on many pupils. Pupils *can* calculate the volume, particularly when the measurements are simple whole numbers – for which we have arranged. Pupils *can* divide the result of their weighing by the result of their volume calculation, particularly when the latter is a round number. But many who can carry out the arithmetic do not see the point of the calculation – they carry it out obediently, without feeling the necessity.

The measuring appears as a fairly interesting routine which does not require much thought, but the calculation of density appears as an unnecessary interruption of the interesting experiments. It seems so simple to us who are teaching to do the division and arrive at a characteristic physical quantity – the aim of much good science – that most of us are tempted to rush the pupils through it. And then, when we find it presents difficulties, we re-do it with greater care – but not with greater benefit to the picture of science that our young pupils are forming.

So the most we suggest with an average group is that when pupils have compared the blocks of the same dimensions we ask them how they can bring the other blocks into the comparison. If pupils do not show interest or give suggestions, we drop the question. If they are interested, if we succeed in making it an intriguing problem to surmount the difficulty, we coax the class into a discussion of ways and means. If necessary we offer the suggestion of finding out how much one little block 1 cm × 1 cm × 1 cm weighs.

Yes. If you had them, you could weigh little blocks like that little cube. But you have not got them. No, we cannot cut them out with a saw. That would take too long and spoil the big blocks. Can you *count the cubes* in a big block without cutting it?

At this point the teacher should draw pictures on the blackboard in a progression of problems, or give problems for homework, such as the following:

Here is a block of wood 2 centimetres long, 1 centimetre wide, 1 centimetre high. Here is a little cube of wood 1 centimetre by 1 centimetre by 1 centimetre. How many cubes are there in this block?...

Here is a block of wood 2 centimetres long, 3 centimetres high, and 1 centimetre thick. If you could saw it up into cubes, how many cubes would you see on the front face? (This deserves a block of plasticine that we can make marks on.) How many cubes would you count altogether?...

Here is a block of wood that is 2 centimetres long, 3 centimetres high, and 5 centimetres thick. How many cubes would you see on the front face? How many layers from front to back? Can you count the cubes altogether?

If this does not lead easily to the idea of 'counting the cubes' by multiplying length by breadth by height, we drop the matter. Of course, children have learnt this in arithmetic class; but it may not have been learnt with meaning; and we are not likely to succeed in attaching a clear meaning in a hurry now.

If the pupils do find it easy to 'count the cubes' in various blocks, then they can do a few division sums to find out how much each cube weighs.

Success at this level is likely to mean either that we have a fast group or that we are already spending more time on density than it deserves in this particular programme.

'Counting the cubes' Some children will need clear *encouragement*: show a centimetre cube and say: 'How many of these are there in that block? Can you *count the cubes* in the block?' If a well-packed box of sugar cubes is available, it will help to illustrate the business of 'counting the cubes'. As one teacher reports, 'it rapidly resolved any lingering doubts'. If, elsewhere in the school, the cubes and sticks of wood that are now used in teaching mathematics are available, these too may help our teaching here. Wooden 1-cm cubes are available cheaply.

Some children will need reminding to measure all three dimensions and not just one or two. It is a great help if the teacher puts a sketch on the blackboard to bring out this need. It is unfortunate that it is cheaper to manufacture rectangular blocks with two dimensions the same. If all three are different, as in our 3 cm × 4 cm × 5 cm blocks, there is less danger of this mistake.

The *Pupils' Text* provides a series of progress questions and questions (numbers 49–54) culminating in the 'Packing grapefruit' problem (54) which can be extended to the atomic case described in Question 55 (optional, for fast groups only). This question is repeated here:

QUESTION 55 *The problem of the atoms*
Scientists can measure the size of a single atom. An atom of iron is so small that if you put it into a small cubical box that would just hold it the box would be about $\frac{2}{100\,000\,000}$ cm wide, and the same thick and the same high. Think of the iron block you handled, it probably measures 5 cm long × 4 cm wide × 3 cm high. Suppose that the atoms are arranged very simply in it in a simple crystal pattern like the grapefruit are packed in the box.
a. How many atoms would there be in the length of your iron block? How many in the width? How many in the length?
b. How many atoms would there be in one layer 5 cm × 4 cm?
c. How many atoms would there be in the whole block?
d. Suppose your block had 450 grams of iron in it. How much iron would there be in a single atom?

The essential part of the problem does not involve density directly but can be done by simple arithmetic. We offer it here as an important problem to encourage children to think about atoms and to give them a first glimpse of the very small size of atoms and the very great number of them in a visible piece of matter. For this we simply announce the 'size' of an atom (of iron) and use that piece of data for a numerical problem. That would give science a very poor reputation if we did it often – teaching by unsupported assertion – but in this case we use it for an early introduction, and within the year children will do a simple experiment to estimate molecular dimensions themselves.

Many children of this age do not have a strong appreciation of very small sizes. This piece of information about atoms may not surprise some pupils and it may not impress many. Yet there will be no harm in carrying out the calculation (providing the teacher gives enough help to get it done fairly quickly without producing headaches); and then a thought about atoms being so small and numerous will be stored up, to be drawn on in future years.

After experience with Question 55, we think it so important that we urge all teachers to use it: but we also know it proves too difficult for many children unless special preparation is given. So we suggest that the main problem (55) should be preceded by Question 53 for homework a *week before*.

We hope that teachers will succeed in coaxing many children through Question 55, estimating the number of atoms, giving as much help as their class needs. (See the note below on help with arithmetic of big numbers.) Even if the work is not fully understood, it will form a valuable beginning provided we give praise for partial success and do not insist on clear understanding yet.

Question 55 is difficult, because its numbers run to such extremes; also, for some children, because it talks about strange things like atoms instead of familiar things like the length of a kitchen table, which have been measured in arithmetic class long ago. This is a problem to let pupils wrestle with, giving some encouragement but not demanding an answer from everybody, and certainly not dictating a properly worked-out answer. Rather leave this problem to go home and be puzzled with. Science is real and earnest and worth puzzling about.

NUMBERS, LARGE AND SMALL

(Optional now but very useful later – especially for those who might proceed to take the 'O' level examination.)

Because we make this early start with atoms, we need to deal with very large numbers and some very small ones. Unless pupils can express them with the powers of 10 as a form of shorthand, difficulties of arithmetic will make this work practically impossible. We hope that after some practice with our preliminary scheme of 'separating out the noughts' pupils will be ready to try the professional way of writing large and small numbers in 'standard form'.

Suggestion for introducing powers of ten
The following informal scheme will help pupils to see the problem and solve it in a simple way, as preparation for a full use of powers of ten with a multiplying number.

We need to deal with very big numbers like 240 000 000. You will soon get tired of writing a number like that in full. Worse still, you will find that multiplying big numbers by each other, or dividing them, is clumsy. It would be much better if we had a short way of writing big numbers. Try this way:

Make a column for the figures and a column for the zeros. Label the left-hand column, FIGURES, and the right-hand column, ZEROS. Then instead of writing 240 000 000 write 24 in the figures column and 7 in the zeros column:

	FIGURES	ZEROS
240 000 000	24	7

Now suppose you want to work out 240 000 000 multiplied by 200 000. Those two big numbers could be written like this:

240 000 000	24	7
200 000	2	5

and the multiplication sum could be written in this way:

240 000 000	24	7
× 200 000	× 2	+ 5
	48	12

In all this business, adding a 0 in the right-hand column means multiplying by 10 so the result of our multiplication sum must have 48 in the left-hand column and 7 zeros plus 5 zeros in the right-hand column.

With a little practice pupils catch on easily. Then we make further advance:

Instead of writing 240 000 000 with those two columns 24 and 7 we can tell the story of the second column in a different way. The 7 in the second column means 7 zeros; but that really means 7 lots of multiplying by ten. There is a professional way of saying 'multiplied by ten seven times', and that is 10^7. If we use that, we can write 240 000 000 as 24×10^7.

After some more practice with that form, pupils may be ready to take a further step – the extension of the idea to very small numbers. Just as 10^2 is a shorthand form of 100, so 10^{-2} is a shorthand form of one-hundredth. Then the size of the iron atom quoted in Question 55 may be written as 2×10^{-8} cm rather than $\frac{2}{100\,000\,000}$ cm.

The step to 'standard form' is a development which can be left at this stage; but the technique is introduced in Question 65. 'Nothing succeeds like success' in this arithmetic as in all teaching. We believe the encouragement of success in these early stages of using big numbers will carry a class through, and make our questions about atoms both possible and pleasing.

Volume and weight

The children have experimented with blocks of various materials and have records of the sizes and the weights of the several blocks. Some of those blocks have different (whole-number) dimensions. With a fast group we let that raise the question of devising a new quantity – density – to make the comparison between the materials.

The teacher should elicit the suggestion that, to find out which materials are denser, we cannot just weigh them but had better find out how much one cubic centimetre of each will weigh. It takes much more time to coax a suggestion like this out of a class, and the coaxing may amount to little more than posing a question and, while waiting for an answer, giving more and more hints as time goes on. Yet with a fast group the question and the waiting do good: they encourage these young scientists to think – and they give a truer picture of science.

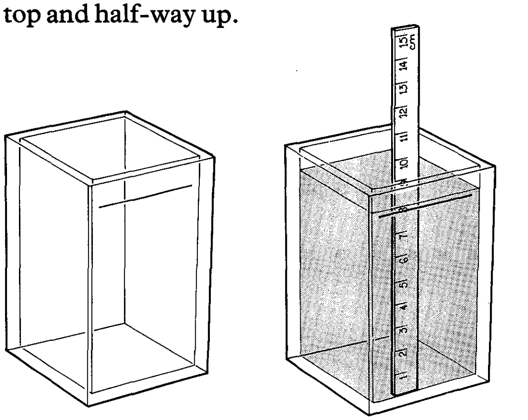
14 Class Experiment
Weighing liquids

APPARATUS *item no.*

16 Perspex containers *26*
8 Lever-arm or simple top-pan balances *42*
16 Plastic measuring rules *25*
1 Chinagraph pencil *543*
Sand and, if possible, wheat, rice, or dried peas
Liquids (for example: water, paraffin, brine, oil)

PROCEDURE

Extend the weighing of samples to liquids by providing a rectangular Perspex box, so that the volume can be calculated easily. That box too should have whole-number dimensions in centimetres. For height, it should be marked inside with scratches, or a mark with a greasy pencil near the top and half-way up.



Here again, we should not spend long on this, or insist on calculations of density. Except with a fast group, our aim is to give a feeling for density of liquids as an idea rather than give training in measurements and calculations.

Children should first weigh this box full of sand, then water, then some other liquids. In the case of sand, and wheat or rice as well, if that is tried, ask:

What does that weighing tell us?... Yes, there are spaces between the grains. I suppose it will lead to an 'average' density for the sand and spaces combined.

What would the density of a sand grain be like?... Yes, that would be different.

Does that same question arise in the case of weighing water for density?

That may raise discussion of atoms again.

Note that this is our general intention, to link together different parts of physics by having the same kind of question turn up many times in different places, leading to growing knowledge, and a growing sense that knowledge of science is connected together. Nothing but the interest and ingenuity of the teacher can really achieve that sense. We may suggest examples here and there; but the real value lies in the cases where the teacher can seize an opportunity or even manufacture one.

Before leaving this experiment, the teacher should show 1 litre of water being weighed in a large plastic box (item 10D).

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15 Demonstration

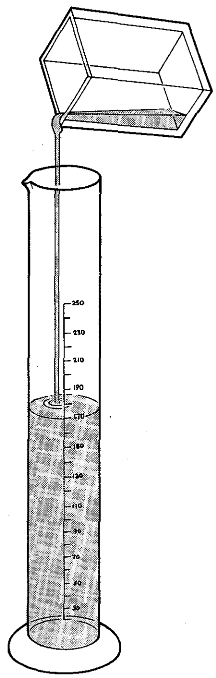
Testing a measuring cylinder *(Optional now)*

APPARATUS *item no.*

2 250-cm^3 measuring cylinders *518/1*
1 1000-cm^3 measuring cylinder *518/2*
4 Perspex containers *26*
4 Plastic measuring rules *25*
1 Perspex box (10 × 10 × 11 cm) *10D*

PROCEDURE AND DISCUSSION

The Perspex container is filled with water to a depth of, say, 4 cm using the special plastic rules which are marked only in centimetres. The volume is worked out. The contents are then poured into the 250-cm^3 measuring cylinder and the level



noted. The process may be repeated, different depths can be tried, the larger measuring cylinder and the larger Perspex box can be used. The teacher can also pour water from measuring cylinder to measuring cylinder.

Since the measuring cylinder is already 'graduated with official marks' children are likely to reverse the treatment and think that the cylinder is checking the box, unless we arrange our teaching carefully to avoid that. It may be our own first impulse as teachers to take the cylinder graduations as correct and argue from them; but that would be a complete change of policy from the intention of our suggested teaching.

Here, we are anxious to develop the idea of *volume* as measured by a simple process of 'counting the cubes'. To bring in a graduated cylinder as authority will either involve πr^2 or require a description of the graduating of such a jar when in fact the latter is exactly what we are demonstrating.

It has appeared that making this a class experiment emphasizes such a treatment of the measuring cylinder as 'right' or else leads to long discussion. Therefore we suggest a quick demonstration experiment here, in which the teacher pours a measured 'boxful' of water several times in succession into a measuring jar. If the water is coloured and an illuminated translucent screen is placed behind the cylinder, the readings can be seen clearly enough for the present purpose. Then the teacher should pour the water from that cylinder into another cylinder of different cross-section and show that the new cylinder's statement of the volume is the same.

Strictly speaking the last part of the demonstration does *not* show that water keeps the same volume when its shape is changed. It only shows, so far as young pupils are concerned, that the two cylinders have both been marked to agree with the rectangular box, on the tacit assumption that the pouring does not alter the volume.

To show that the volume of a sample of water remains constant, is independent of the container, we should use several different rectangular boxes. Teachers may find it interesting to do that, because it raises an idea which is unfamiliar to some children of this age, but we urge that it should be restricted to a quick demonstration if tried at all. (It is difficult to obtain an assortment of transparent rectangular boxes with integral centimetre dimensions; and we hesitate to recommend doing this with other boxes which would involve considerable arithmetic.)

Children's ideas of volume It is often taken for granted that the concept of volume is intuitively clear; but some children need experience here. Some experiments have shown that quite apart from a quantitative understanding of 'volume' children do not develop the idea of volume (e.g. of some liquid) being invariant of their own accord in the early school years. Up to an age not far from that of our present pupils, it is not a property of Nature that is obvious, or quickly learnt and understood by experience, that when some water is poured from one container into another its volume remains the same. The tall column in a narrow cylinder does not look as if it has the same volume as the short column in a wide cylinder. Far from regarding that as an optical illusion, young children may regard it as a demonstration of a change of volume.

We should reflect that the surface *area* of the liquid does change. Or, if we keep to two dimensions, the *perimeter* of a loop of string is independent of the shape enclosed, but the *area* is not. Thus it is we as scientists, and our scientist ancestors, who have selected volume as an important thing to deal with because we find it is invariant. In fact, we only find volume invariant because we deal with many materials that are almost incompressible. If all the materials in common use were gases, or squashy solids like rubber foam, the invariance of volume would not be a common experimental property; and we certainly should not install it as a basic geometrical property.

When we reduce our thinking about volume to a drawing of little unit cubes in any solid space and a counting of those cubes, *volume* looks to us as if it must be something that keeps the same total, even when the shape is changed. But in thinking that, we are playing in imagination with those little cubes and assuming that the number of them stays constant when we move them about to make a different shape. A down-to-earth question: 'What *are* the cubes; what are they made of?' brings us back to the properties of matter in this world. We realize that we are thinking about cubes of solid and liquid materials which are incompressible. Therefore we should not be surprised – or worried – if we find young pupils have not yet generalized from experience of Nature to regard volume as invariant. They do not even regard it as interesting – nor, perhaps, should we, if it did not in practice have the invariant property. On the other hand we may well expect pupils to join us as they grow older in taking volume to be a constant property of many materials; that will develop as they do more experiments or learn more about practical things in the world. Other quantities, such as surface-area, do not keep the same value when a piece of material is pushed into a different shape. (And in two dimensions, a loop of string has practically the same perimeter whatever shape it has on the table, but its area changes as the shape is changed.) So we should regard growing knowledge about volume, etc., as something to wait for, rather than something to teach insistently now.

Cognitive psychologists have done interesting and important work in observing the development of concepts such as this idea of invariant volume; but there are differing schools of thought concerning the results. The observers have tried to find out what it is that children understand, at a given age, *when they have been taught in conventional ways*. There are teaching experiments, including our own, which offer, in essence, to alter the data which have formed, so far, the basis of the research of those observers. If such teaching furnishes experience which few children now have, then in the future observers may observe quite different things. We therefore believe that in making changes of method and attitude such as ours, we are not justified in making strong positive or negative predictions of what can be done at each age. We believe that the only way to find out how and when various things can be taught successfully is to try various ways of teaching them.

Whatever our pupils think at their present age, that they will join us in thinking volume invariant as the years go on will be of great general value to their understanding of science, because we are concerned with describing Nature by stating the things that remain constant; but we can safely leave Time to teach that. At most a few quick demonstrations with gentle commentary or a question are all that are likely to be needed here. And all that those will really show is that water is incompressible.

WEIGHING AIR 'How much would all the air in this room weigh?'

At this point raise the question of weighing air itself. Point out that the laboratory has a good motor-driven pump that can pump the air out of things quickly. And ask how we could use that for a weighing of air.

Of course, we as physicists are going to weigh the air in order to measure the density of the air. But remember that 'density' is an artificial concept for children and perhaps not a very interesting one. On the other hand 'weighing some of the air in this room' sounds a much more interesting operation and we should start by asking for guesses of the weight of air in the room.

While we wait for suggestions from children about methods of weighing air, some will ask how we know that the pump has done its job. At once give a demonstration of a bottle being pumped out by the pump and then opened under water. Water with a little ink will make the experiment clearer.

16a Demonstration
Pumping air

If this experiment (Investigation of an evacuated bottle labelled 'vacuum') was done earlier in the course, where it was marked 'Optional now', it need not be repeated here and the class can move on to Demonstration 16b.

APPARATUS *item no.*

1 Ordinary bottle of clear glass with a well-fitting rubber stopper
1 Motor-driven vacuum pump *13*
About 1 m of pressure tubing *10DD*
1 Large transparent trough *532*

PROCEDURE

The rubber tubing is connected to the vacuum pump with the clip open. The bung and glass tube must be tight fitting. Old or perished rubber bungs or tubes should be rejected. The air is removed by pumping and the clip on the rubber tubing is then closed.

To show that the air has been removed, the neck of the bottle (including the rubber tubing) is immersed under coloured water and the clip is removed. Water will rush in to fill the space. If the vacuum is a good one there should be very little air inside the bottle. If the pump was not very effective or if there was a leak, then the water will not completely fill the bottle and some air will be seen in it. There will always be a small bubble left, however well the bottle is evacuated, due to air that was dissolved in the water.

It is essential to repeat the experiment without pumping air out of the bottle before immersing it, in order to show what happens in that case. This should be done second to avoid using the pump with a wet bottle.

We ourselves may take vacuum pumps for granted, but to children the idea of taking away invisible air is strange. To help them to visualize the process, show the following demonstration: Pump smoky air out of a flask. (A very good way of filling the flask with smoke which will not hurt the pump is to put cigarette smoke into it. More roundabout methods of producing the smoke may well divert pupils' attention to the chemistry.)

16b Demonstration

APPARATUS *item no.*

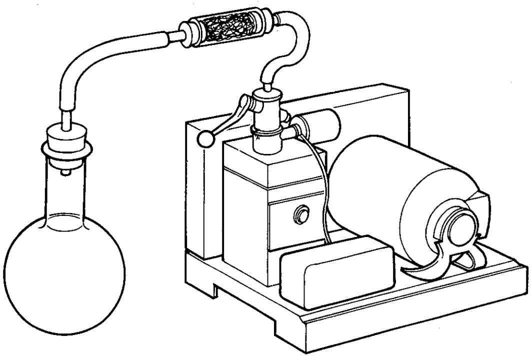
1 Vacuum pump *13*
1 One-litre round-bottomed flask *10K*
1 Bung with glass tube to fit *10L*
1 Smoke filter *10CC*
1 Length of pressure tubing *10DD*

The vacuum pump should be a motor-driven rotary pump and *not* a hand pump.

PROCEDURE

Visible gases such as bromine are highly corrosive and should not be used with school pumps. However, smoky air can be pumped out of a clear flask without harming the pump if a smoke filter is inserted between flask and pump.

The smoke filter is made with a 20-cm length of 4-cm diameter glass tubing containing glass wool. Bungs are provided at each end through which glass tubing connects on the one hand to the vacuum pump, on the other to the flask to be exhausted.



Some cigarette smoke (or smoke from a smouldering drinking straw) is blown into the one-litre round-bottomed flask so that it is clearly visible. The flask is closed with the rubber bung through which a glass tube is connected by rubber tubing to the smoke filter, which in turn connects to the pump.

The pump should be switched on so that the smoke can be seen being pumped out. The needle valve on the pump should be adjusted so that the rate of pumping is as slow as possible, otherwise the operation is over too quickly. Where the pump is fitted with a gas-ballast valve, this should be left open during this process.

It is helpful to illuminate the flask brightly and to have a dark background.

NOTES

1. For connection to the vacuum pump it is essential to use pressure tubing.
2. Glass wool is used inside the smoke filter (as described above), as has been a standard practice for years. Glass wool is unpleasant to handle and obviously it should be left inside the glass tube containing it.

16c Demonstration

Pump air out of a polythene bottle, or out of a hollow doll made of stiff rubber or a large syrup can. This experiment is usually done to demonstrate the effect of atmospheric pressure outside; and it should probably be repeated later when we come to that. Here attention is directed to the pump taking away something from the inside.

APPARATUS *item no.*

1 Polythene bottle or large syrup can (4 to 5 litres)
1 Vacuum pump *13*
1 Rubber tube and bung to fit bottle or can
1 Length pressure tubing *10DD*

PROCEDURE

A rubber bung with a glass tube through it, to which is attached pressure tubing, is used to connect the bottle to the pump. The air should be removed from the bottle (or the syrup can) so that it collapses.

We must be patient in discussing the idea of a vacuum. It does not occur naturally to children; and when they have been given the idea they still do not picture it easily. It is an artificial intellectual concept. We must welcome pupils to join us in adding it to the scientific vocabulary but we must respect their doubts. Remember that they take the air itself for granted as invisible and almost absent, as did our ancestors, including the great Greek philosophers. It was only at a late stage in the development of physical science that men realized that we live at the bottom of an ocean of air, which has density and exerts pressure.

The pump Pupils may ask what the pump does when it pumps air out. We should not divert the whole discussion into a study of air pumps at this stage; but now or later we should say something to avoid the idea growing up that the pump pulls the air out, like a winkle out of a shell, by a mysterious process of attraction called 'suction.'†

The following description is near to the action of a mechanical vacuum pump, and it may help to continue thinking about gas molecules – but since it trades on the idea of molecules, it must wait until a little later.

The pump acts rather like a lift that is getting people out of the top floor of a tall building. A lift doesn't pull the people out. It just offers them a chance to get in the lift, and then the lift carries them out.

The lift goes up to the top floor, the lift man opens the door of the lift and waits till a few people have wandered in. Then he slams the door shut. Down goes the lift. Out go the people; walking out if they are human beings, but pushed out by a moving piston in the case of air molecules in the pump. Up goes the lift again; open the doors; more people wander into the lift; slam the door shut; down goes the lift; out go the people. Up goes the lift . . . and so on. Think of that happening with a pump taking out air molecules, batch after batch in trip after trip. At that rate you would never get *all* the molecules out; but our pump does a very good job and makes what we call a good vacuum.

How can we weigh air? Repeat the question, 'How can we weigh the air in a box?' and if possible leave that question to simmer at home over a weekend. Thinking about problems like that and their possible solution is the work of a professional scientist, and there is no reason why children should not share some of that even at this early stage.

The simple method of weighing a Perspex box before and after pumping the air out is difficult, because a big box will collapse‡ and a little box shows a very small change of mass.

17 Demonstration

First attempt to weigh some air

APPARATUS *item no.*

1 One-litre round-bottomed flask *10K*
1 Bung and tube to fit flask *10L*
1 Vacuum pump *13*
1 Lever-arm balance *42*
1 Perspex box (10 × 10 × 11 cm) *10D*
1 Length pressure tubing *10DD*

PROCEDURE

A one-litre round-bottomed Pyrex flask weighs approximately 350 g. The change in weight when the air is removed is of the order of 1.2 g. Instead of the Pyrex flask, some teachers prefer to use the squash bottle which was used earlier in the year.

On the single-pan balance, which has been used throughout the course, this amount will scarcely be appreciated. The object of this experiment is to show how small the weight difference is, in fact too small for our balance.

The flask must have a well-fitting rubber bung with a glass tube through it, to which is attached a rubber tube with a screw clip.

The flask is weighed. The rubber tubing is attached to the pump and the flask exhausted. The flask is re-weighed. (The volume can be found by filling the flask with water and pouring into the rectangular Perspex box.)

NOTE

For connection to the vacuum pump it will be necessary to use pressure tubing.

The weighing and the volume measurement present difficulties here for children. The principle of the latter is apt to get lost in a lot of water pouring. It is probably better to pump extra air *into* a container to give a reasonable increase in weight,

† Some teachers wage a vigorous war against 'suction' as being a mistaken idea. Others now consider that 'to suck out' is a technical term meaning 'let the atmosphere push'. And they may be wise to save time and trouble like that. Their pupils will not grow up thinking that 'Nature abhors a vacuum' or that the mercury in the barometer is held up by invisible spider threads. As in the general use of language, we may be wise to let some slang terms come in to common use, or rather to approve them when they have been in common use long enough. We might perhaps regard 'suction' as a second-class technical term.

‡ The suggestion of weighing a balloon empty, then blowing it up full of air and weighing it again may arise. Teachers will remember that this is the fallacy quoted by Galileo. A bladder full of air gives the same reading on the balance as it does when squashed flat. Reason: the buoyancy of the surrounding air just compensates for the weight of the air inside in the first case. A rubber balloon does weigh a little more when inflated, because the air inside is at slightly greater pressure; but that is not sufficient for use here. The volume of the container must not change much between our two weighings.

and measure the 'ordinary' volume of that extra air by letting it out into a measuring vessel under water.‡

If this latter vessel is a transparent rectangular box, its volume can be measured easily without any intermediate method. If children can suggest that procedure, or even any part of it, the suggestion is well worth waiting for, even for a whole week, because during that wait children in the class have time to realize what the problem is. Coaxing may be needed. A terse announcement 'the proper thing to do is to let the air out and measure it' spoils the fun of being a scientist and leaves some pupils confused.

18 Demonstration

A second attempt to weigh some air

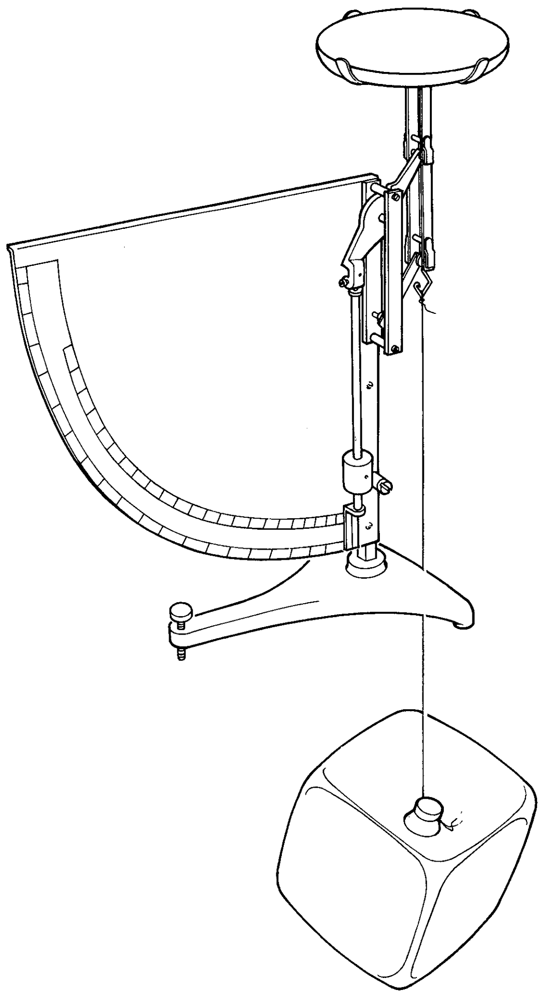
APPARATUS *item no.*

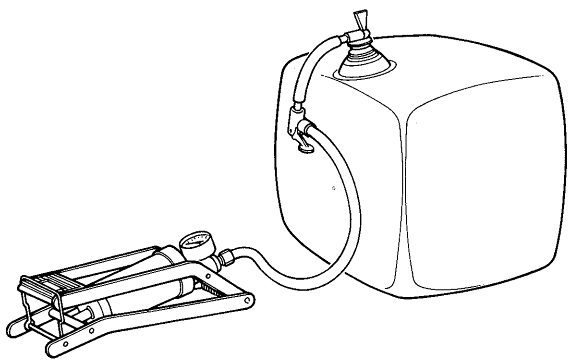
1 Plastic container with tap (about 30 × 30 × 30 cm) *10E*
1 Foot pump *45*
1 Perspex box (10 × 10 × 11 cm) *10D*
1 Balance *42*
1 Large transparent trough *532*

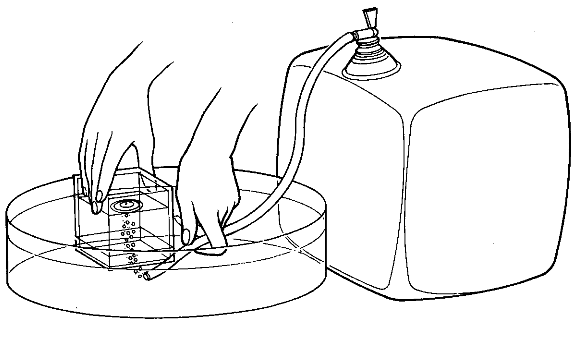
It is recommended that a second spare plastic container should be available.

PROCEDURE

The plastic container is pumped up to an excess pressure of about half an atmosphere (corresponding to about an additional 8 g of air) and weighed on the balance. In the case of the lever-arm balance, this is best achieved by hanging the







container below the pan. Then the extra air is carefully let out into the measuring box under water, in several fillings. When no excess air will come out, the container is weighed again to find the mass of air released. Making the weighings in this order, rather than weighing the container 'empty' first, is found to make things clearer for the pupils.

The success of this experiment depends on pumping enough air into the large container to

‡ Teachers are familiar with the usual method for collecting gases by displacing water from an inverted jar. But this is an entirely strange idea to children of this age. Even those who have seen an inverted bottle providing water for chickens will hardly think of applying it here – and they would probably expect it to fail, since in the device for chickens air does not bubble in freely. Therefore we need to introduce the idea carefully, perhaps with a preliminary demonstration of blowing bubbles in by a tube from the mouth.

show a clearly measurable difference in weight. The containers suggested for this experiment are intended to carry liquid so one does not know whether they will stand a large excess of air pressure. Careful tests show that an *excess* air pressure of $\frac{2}{3}$ atmosphere above atmospheric is quite safe. Even if a container is pumped until it gives way, the bursting is not in any way dangerous.

However, if one has only a single container, one must feel anxious about pumping it up, since when one does discover the limit it is too late. Therefore we urge teachers always to have *two containers*, one for use and one as a spare in case of trouble, and as a reassurance to encourage considerable pumping. The container suggested can take 8 to 12 g excess air.

Weighing this large container on a lever balance may itself introduce serious errors if the container is simply placed upon the pan of the balance. It must be hung by a string from a suitable central point under the pan so that the balance is loaded in exactly the same way for both weighings.

'The air that is inside the box is compressed, so what is its "ordinary" volume? How could that be found?' This is a question to discuss with the class and let them think about. It is simpler to ask: 'How can we find how much extra air we put in?' Finally the class should be led to suggest letting the excess air out into another container, a rectangular one, in which it can be measured at atmospheric pressure. That suggestion is worth waiting for, because the children then have time to realize what the problem is.

From the measurements the pupils should work out the weight of a litre boxful of air and hence the weight of 1 m^3 of air.

The air in the room As soon as the weighing is done, ask how much the air in the whole room weighs. The children will require to estimate the length, breadth, and height of the room in metres and then to use their recently acquired knowledge of the weight of 1 litre of air. Then discuss the idea of extending that to include the air in the room above, and on up and up . . . and raise the question of atmospheric pressure. Do not go further with that now, but promise to return to it later.

The notebook record When the method is evolved and the weighing done, pupils should record the measurements briefly and neatly in their notebooks.

From now on we should encourage the children to make neat, legible notes of their observations as they actually occur, so that there is no need to make fair copies of rough work. This method encourages honesty, saves time and is good training in self-reliance. Simple diagrams, preferably drawn free-hand to save time, can replace a lengthy description. There is no point in a notebook doing duty for a text.

For example, a few lines would suffice for a pupil's description of the experiment, if accompanied by one or two informal sketches. If each pupil writes his account *in his own words*, it will be far more valuable than any dictated account, even an informal one like the specimen shown overleaf. Pupils are 'doing science', not 'being trained'.

In thinking about pupils' notebooks, we should not hark back to our own records in a university laboratory, because even those were the product of a formal tradition. We should rather steal a look, as perhaps we did then, at the notebook of a research scientist busy in his lab. That notebook is usually quite a simple affair: fairly neat, informal, not embellished with drawings made with rulers and coloured pencils, nor headed with a list of 'apparatus used' – such a list is an artificial discipline – if a temperature is recorded it is obvious that a thermometer was used; and it makes physics seem an artificial business, far from the real physics that we know, when we insist on such formalities. The key things in the research scientist's notebook are actual records of observations. If you look at it you will think the book is the diary of a busy scientist. We can easily encourage children to keep an equally informal, but even shorter, diary and that will bring them much nearer to an understanding of science. And it will be a diary that they will preserve.

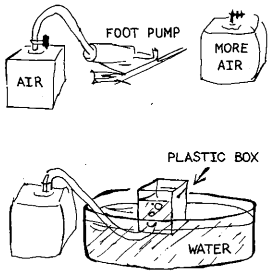
SPECIMEN OF A SIMPLE NOTEBOOK RECORD WHICH A PUPIL MIGHT MAKE FOR THE DEMONSTRATION EXPERIMENT OF WEIGHING AIR

(This suggested record is intentionally given an informal style and we hope that teachers will experiment with even simpler requirements)

Specimen description (in words)

We pumped air into a big (plastic) box, until the box had a lot of extra air in it.
We weighed the box before and after the pumping.
The box weighed more after pumping. We think the extra weight must be the weight of extra air pumped in.
Then we let the extra air out through a pipe into a 'square' box filled with water. There was so much extra air that we filled the square box several times. We counted how many times we filled the box with bubbles of air, and we measured the height of air in the box for the last lot of all. Then we could 'count the cubes' of air that came out when we let it all out.

Specimen description (in sketches)



Specimen record (written on opposite page of notebook)

Big box WITH extra air weighed	248 grams
Big box, AFTER extra air had come out, weighed	240 grams
Extra air from big box filled the 'square box'	6 times
And then once more but only to a height of	5 cm

So $6\frac{1}{2}$ boxfuls held 8 grams of extra air

$$\frac{8}{6\frac{1}{2}}$$

= 1.2 grams of extra air.

The inside of the square box measured 10cm × 10cm × 10cm
Therefore each box had 10 × 10 × 10 small cubes
that is 1000 small cubes each of 1 cubic centimetre.
Therefore 1000 cubic centimetres of air weigh 1.2 grams.

SOLIDS, LIQUIDS, AND GASES

Collect together the weights of a litre of various materials and ask for suggestions of additions to the list. If necessary, just announce some typical values. Encourage some rough estimates and include some rock materials from the Earth's surface. Here are some examples.

Weights of 1000 cm^3 of:

brick	1.6 kg
concrete	2.3 kg
earthenware	2.8 kg
glass	3.2 kg
granite	
limestone	

Ask the class if solids, liquids, and gases in general differ greatly in density. We are going to use that for an important discussion, so it may be best to let children think out their own answers by doing a problem for homework before we discuss any more.

Gases appear to be markedly different from solids and liquids; we may ask for ideas about gases in terms of 'atoms' or 'molecules'. Ask how suggestions might be tested. This question, having been raised, should be left for a while.

Melting and evaporation Discuss the possibility of turning solids into liquids and then to gases. Give pupils as a class experiment small samples of lead, iron, ice, etc., to melt in a Bunsen flame. If there is time, let them melt some sulphur in a crucible and make monoclinic crystals of sulphur, and refer back to crystal studies.

Ask children to watch, and feel, water or alcohol evaporating from a wet finger.

19 Class Experiment
Melting and evaporating

APPARATUS *item no.*

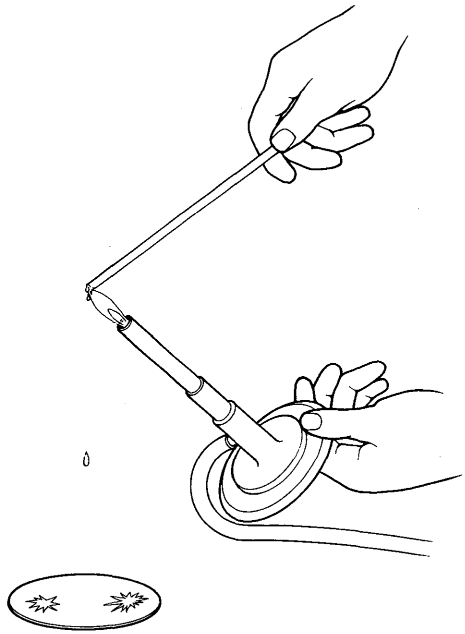
16 Pyrex test-tubes (say, 75 × 10 mm) *546*
16 Test-tube holders *526*
16 Bunsen burners *508*
16 Heat-resistant mats *509*
16 Beakers (400 cm^3) *512/2*
16 Tripods *511*
16 Microscope slides *3G*
Ice
Solder (not cored)
Lead strip
Iron wire or steel wool
Sulphur
Naphthalene

PROCEDURE

The following experiments should be tried, the order does not matter:

1. Put ice in the beaker and stand on a tripod over a Bunsen. Watch it melt.
2. Repeat with sulphur using a slightly hotter Bunsen flame. If time allows, watch the sulphur cool and see monoclinic crystals of sulphur forming: this will remind pupils of the earlier work on crystals.
3. Hold the Bunsen at 45° so that the centre of the flame is vertically over the centre of a heat-resistant pad. Adjust the Bunsen flame for the highest temperature. Stick the end of a short length of solder into the flame. Molten solder will splash on to the pad. Resin-cored solder may make small flashes of flame, so pure solder should be

used. The Bunsen should be at 45° to avoid solder falling back into it.



4. As 3, using a short length of lead strip either held in a Bunsen flame or placed in a tin-lid with the flame directed on it.
5. As 3, using iron wire. Pupils might try copper wire too.
6. Boil a little water in the beaker or test-tube. It takes a few minutes to boil dry. This experiment could obviously be a continuation of 1 provided only a little ice was used.
7. Put a few drops of alcohol (methylated spirit) on to a piece of glass and see how quickly it evaporates to dryness. It helps to blow gently on it. Water will also evaporate in this way, but it takes much longer. Pupils should also dip their fingers in alcohol and water and observe the evaporation.
8. *(Optional)* Heat some crystals of naphthalene in a test-tube. This must be done in a test-tube as molten naphthalene catches fire in an open dish. Alternatively, the tube containing the naphthalene may be heated by holding it in a beaker of boiling water.

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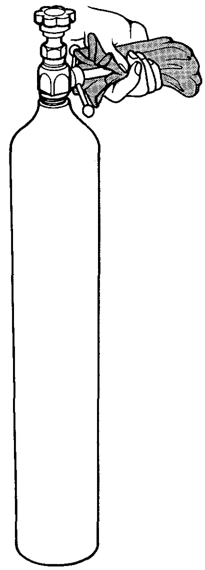
20 Demonstration
Solid carbon dioxide turning to a gas

APPARATUS *item no.*

1 Carbon dioxide cylinder *19/1*
1 Dry ice attachment *19/2*
1 Balloon

PREPARATION OF SOLID CARBON DIOXIDE

To obtain some solid carbon dioxide from the cylinder, fold a piece of closely woven cloth (preferably of dark colour) in the form of a bag. Hold this bag tightly round the nozzle of the cylinder and open the valve at full blast for five to ten seconds. Where the cylinder is of the siphon type it should be kept upright, but if it is an ordinary cylinder it should be held upside-down during this process.



PROCEDURE

Scrape some solid carbon dioxide 'snow' out of the bag in which it is made and insert a little in a container which is able to show expansion.

The easiest container to use is a toy balloon. The neck of the balloon is stretched and held open by several fingers and half a teaspoonful of the 'snow' is quickly poured in. At this stage the balloon is practically flat, with no volume inside. The neck of the balloon is quickly knotted and tied. As carbon dioxide changes from solid to gas the balloon inflates, showing a large change of volume. As an alternative, a polythene food bag may be used; but it is harder to knot and tie up the neck of that sufficiently well. The bag must be tested for pin-holes, under water, beforehand. Whichever is used, balloon or bag, knotting is essential. (Note that the change of volume is about 1 to 600. Therefore the balloon is likely to grow, at most, to 8 to 10 cm diameter.)

Alternatively, let a small block of solid carbon dioxide evaporate. Compress some 'dry ice' into a small cube of about $\frac{1}{2}$ cm^3 volume, place it quickly under the mouth of a gas-jar full of water that is inverted over water. Let the gas bubbles collect.

Models: a picture of solids, liquids, gases

There may be the suggestion that gases are made of particles farther apart than those in solids and liquids. It may be useful at this point to say:

Suppose each of you were a molecule. Suppose the whole class are the molecules of a piece of some stuff. If the stuff is solid, how would you look? Stand in the middle of the room and show me how you would be arranged as a solid.... Now show me how you think you would be arranged as a liquid.... Would you really be farther apart? What happens to a piece of ice or wax when it melts? Now show me how you would look if you were molecules of air or of some other gas.

Here, we are asking for, and giving, pictures of molecules:

in a solid, crowded close in regular array;
in a liquid, crowded close but arranged irregularly and able to move about;
in a gas, far apart.

So far we do not mention the motion of the molecules. Then we may ask why heating a liquid should separate the particles into vapour, but we should not answer that question now. Such unanswered questions are part of learning science as a scientist with a spirit of enquiry – we should tell the children that.

We could proceed to discuss gases and molecules, in a qualitative kinetic theory, but this is probably the time for a change, to leave discussions and unfamiliar ideas and embark on some simple doing, simple constructing with fine fingers that does not need much reasoning.

CHAPTER 2

Weighing small things

Or how to make a microbalance

We provide materials for a simple microbalance – a drinking straw for a beam and a needle for a pivot. We show a specimen ready-made, then give each child materials and plenty of time and encouragement. Then we suggest weighing a grain of sand, a hair.

But, 'where are the weights?' We offer materials to make the weights from sheets of paper.

21 Demonstration

Simple weighing

As an introduction to a class experiment in which children will enjoy making a delicate instrument for themselves, we give a demonstration of weighing things with a simple lever balance. That should be simple, crude, clear; so we suggest a plain beam of wood, like a metre rule but *without graduations*, drilled with holes to receive hooks at the centre and near the ends. For demonstration, we recommend that the apparatus should be large and robust.

The teacher should ask, 'How can I weigh a small parcel, a letter, etc., if I have a seesaw like this and a collection of weights?' (Note that this is placed much earlier than the class experiment that looks for a 'lever law' because here we want to use pupils' common knowledge; so we must use equal arms.)

APPARATUS *item no.*

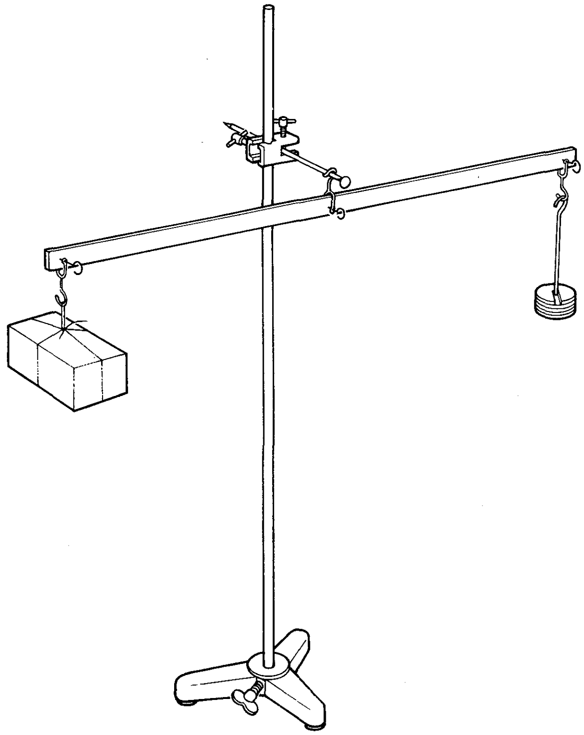
1 Crude balance *10C*
1 Retort stand, boss and clamp *503–506*
1 Weight hanger with slotted weights (10 g) *31/1*
1 Weight hanger with slotted weights (100 g) *31/2*

Also required are objects for weighing, such as a small parcel (about 500 g) and a letter (about 22 g).

PROCEDURE

Suspend the simple lever by one of the hooks positioned centrally. It is convenient to support the hook from a clamp attached to a retort stand by a boss.

The other two hooks are positioned near the ends of the lever equally spaced from the centre.



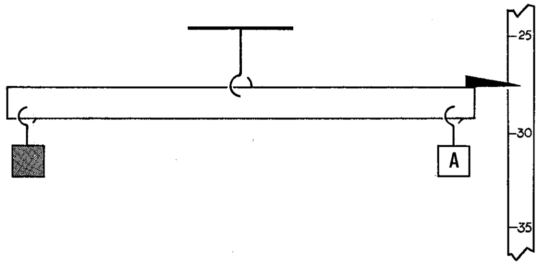
1. Weigh a small package to the nearest 100 g, using a 100-g hanger and slotted weights.
2. Weigh a letter to the nearest 10 g, using a 10-g hanger and 10-g slotted weights.

The first two weighings are done by 'tipping the scale' using various known weights on the other side of the seesaw. A seesaw that is sensitive enough for one job is likely to be too sensitive for the other. In that case, the teacher should change the sensitivity by adding a small load (plasticine or a screw) on the lower edge of the beam at the centre, to bring the centre of gravity down; or, better still, he should drill another hole in the central region above the hole provided.

3. Ask how one could find out whether a letter to the Continent weighs more than the limit for the cheapest stamp, which is 20 g. How could one do this with nothing but 10-g weights, and no smaller ones? Show how this can be done by interpolation (without calling it that).

The teacher must explain: 'Now I will show you an entirely different method. Put a counterpoise on the left and try 10 grams, 20 grams, 30 grams on the right, and mark the pointer positions on a paper scale behind the other end.'

The third weighing shows excess weight by the tilt of the beam, a small pointer attached to the beam reading on a home-made vertical scale. For a scale like that shown in the sketch, to cover the



range needed, we start by hanging 20 g on the left-hand hook and another 20-g weight on the right-hand hook where the letter will presently be placed. The beam will then be almost level, and we mark the 20-g point on the vertical scale. To mark other points on the scale, we keep the left-hand load at a standard 20 g (as we shall do when we come to weighing our letter) and we change the right-hand load to 30 g and put a 30-g mark on the scale. We change the right-hand load to 10 g and put a 10-g mark on the scale. Then we are ready to weigh the letter itself by hanging it on the right-hand hook, still keeping the 20-g 'counterpoise' on the left.

To make a success of this experiment, the teacher will need to prepare the beam quite carefully so that he can make it much less sensitive, bringing the 10-, 20-, 30-g scale into a reasonable range. That simply needs a move of the central pivot to a higher hole, or the adding of a considerable load under the beam at the centre. A large bulldog clip with a piece of metal anchored to it will make the latter change easy.

It is important to arrange the balance like that so that it can be used for all of the demonstrations without delays or special explanations.

4. Then ask if one could weigh still smaller things on this balance: a ring, a pin, a hair? Try hanging a hair alone on one end of the balance. This demonstration should be done very quickly and lightly: it is only intended as a quick introduction to the class experiment, to set the stage for the microbalance.

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22 Class Experiment

Making a microbalance

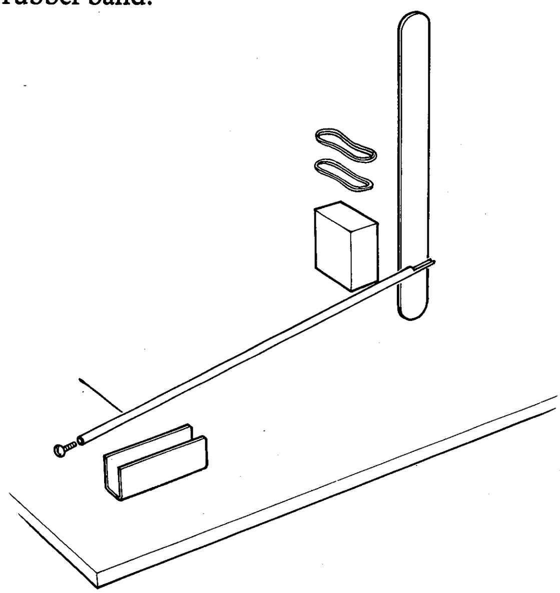
APPARATUS *item no.*

1 Microbalance kit *4*
including:
36 Wooden blocks *4B*
36 Wooden strips (for example, medical tongue depressors) *4C*
36 Elastic bands (5 cm) *4D*
36 Needles (fine) *4E*
36 Metal screws (about 12 mm long and of a diameter to fit the drinking straws) *4F*
36 Aluminium supports *4G*
240 Drinking straws *4A*

There should be one balance for every pupil.

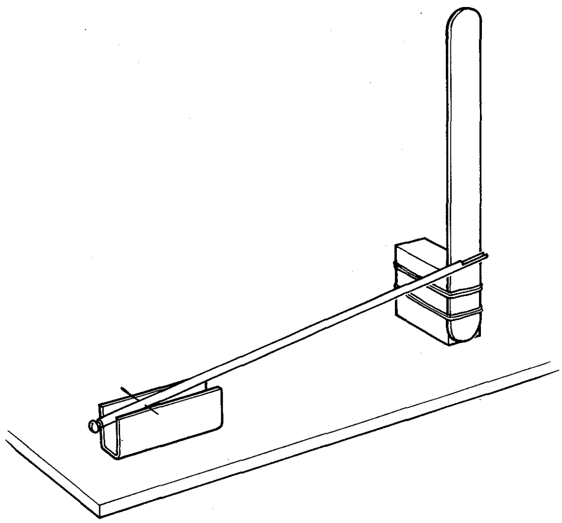
PROCEDURE

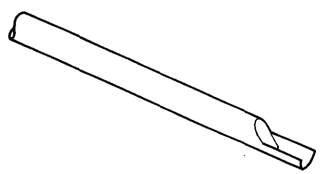
Each child will need a piece of metal channel to form a base on which the moving part of the balance rolls; a drinking straw, to be pierced with a fine needle for axle; a small metal screw to be inserted as a counterpoise in the short arm of the straw; a piece of card to make a scale for the end of the long arm of the straw. The metal channel can be replaced by a pair of microscope slides held on the sides of a wooden block by a rubber band.



The owner should cut away part of the straw at the end of the long arm to make a little scoop in which the things to be weighed can be placed.

The needle which acts as rolling axle for the straw must be pushed through the straw *just above* the long axis of the straw. It is better if children find this out for themselves, but many will need the help of having it pointed out. After that they should find by trial just how high up on the cross-section of the straw to put the needle – that, of course, determines the sensitivity.





It is difficult to make the hole at just the right place and many a straw will be spoiled. The teacher should give out extra straws freely and encourage children to make a good balance without worrying them with the idea of getting the axle right straight away.

Ask each child to weigh one or more grains of sand on his balance. The cry will arise, 'Where are the weights?' Offer a piece of paper about the size of a postage stamp and ask if that will do. 'But how much does that weigh?' 'I don't know, but I cut it from this sheet of graph paper; and I can give you a whole pile of sheets like this, if you like.'

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23 Class Experiment
Making weights for a microbalance

APPARATUS *item no.*

1 Packet of special graph paper *10B*
1 Stack of loose sheets of same paper *10B*
1 Lever-arm balance *42*
8 Scissors *529*
32 Microbalances *4*

The packet of special graph paper should consist of 100 sheets Sellotaped together and marked with the number of sheets. A suitable size is 20 × 20 cm with 2-mm squares. These should be completely ruled so that there are no margins at the edge.

NOTE

It is not possible for manufacturers to supply this graph paper with the weight held accurately to 300 g per 100 sheets. Changes in humidity and details of manufacture will make batches vary from each other. Since this is only a quantitative extension of the main experiment – which is for each child to construct his own microbalance and make it work – we should not insist on great precision in making the little weights for the balance. Teachers, themselves, will appreciate the wisdom of using a rough round number, 300 g per 100 sheets, so that the calculation of the size for a 'unit weight' is easy. However, pupils may well be dismayed by this 'inaccuracy' of taking 300 g as a close enough measure for, say, 275 – the 8 per cent difference might seem to them to spoil the experiment, unless they are already in the right frame of mind to accept it. Therefore we suggest that teachers should discuss this matter of accuracy and a rough round number with pupils before starting on the making of weights. By advertising the advantage of taking a round number and giving some assurance that the weights will still be very useful, teachers can avoid some unhappiness and save considerable time.

PROCEDURE

There should be on a central table plenty of sheets of paper of some standard kind and there should be a pile of 100 sheets (or 200 or 500), with the number of sheets clearly marked on the pile, tied together by Sellotape so that the whole pile can be weighed.

Do not tell the children at once that they will have to weigh the whole pile and do some arithmetic, but let them think of that if possible. If some fail to think of it and look discouraged, help them privately. Then, with encouragement, children will start making various fractional weights.

With slower groups the making of known weights may prove too difficult, even with special graph paper that gives round numbers. Rather than spoil the experiment by letting the weight-making take too long, we should tell children to take one little square of graph paper as their standard weight. They should call it 'one square-weight'. Then they will be weighing in arbitrary units but that will detract from the experiment much less than we expect.

The scale should be graduated by placing 1, 2, 3, . . . (or for less sensitive balances, 10, 20, . . .) in the scoop in turn.

(It would be possible to use a weight as a rider on the straw, instead of placing it in the scoop. That would enable one rider to provide a scale of weights. However, these young experimenters will find that an additional thing to understand; so we advise strongly against that.)

According to their skill and success, children's balances will vary in sensitivity. Suggest as things to weigh: a hair; a dead fly; a grain of sand or perhaps 10 grains; possibly a tiny paper beaker, first with air and then with carbon dioxide.

If 10 grains of sand are weighed, ask for a rough estimate of the number of grains in a handful of sand. Or ask how big a pile of sand would have a million grains. Some children may want to weigh several collections of 10 grains of sand and that will raise some statistical questions if you like.

Above all, this little balance is a thing to make oneself and enjoy having, rather than something that is annoying because it is too difficult, or spoiled because someone else makes it for you or someone else asks difficult arithmetical questions over it. In fact, this balance illustrates a very important general principle about experiments and topics in this course – or in any science course that one is trying out: one cannot judge its full value until the second round of teaching it over again. When one has tried it the first round and learnt how long it takes, and how to be patient with questions, how to praise the results and what a delight the owners have, it becomes much easier and even more effective the next time.

Much of the enjoyment, once the balance is made, comes from making one's own choice of things to weigh. However, teachers may wish to keep a number of suggestions up their sleeve with which to encourage some children, such as:

a flake of mica; an inch of thread; a tiny piece of iron wire which is allowed to rust and then re-weighed – a beginning of microchemistry; a drop of olive oil $\frac{1}{2}$ mm in diameter.

General comments on the use of the microbalance in class

We hope that each child will be able to take his own microbalance home and keep it. Therefore, where several classes are doing this year, it is essential to have multiple supplies of straws and needles. Multiple supplies of the wooden sticks are not essential because children can make their own scale markers at home. Multiple supplies of metal channel are not essential, because a match box will do instead, or children may devise an arrangement such as two bits of wood strapped on to a small block of wood with rubber bands or Sellotape.

The teacher should show a microbalance already made (or possibly one like it that is not quite such a good design but contains opportunities for children to suggest improvements). Each child should have his own materials, and plenty of time. Only a real trial with real children will convince one how long that time must be – and after one has carried it through with a class one will agree that the time was worth spending.

(In preparing for this experiment, the teacher should remember that each child uses one straw and needs another one as a spare, and that children are likely to want to store their balance or take it away; so if several classes are doing this experiment a new set of straws will be needed for each. And spare loading-screws will be needed. It is not safe to rely upon a local supply of straws, because the screws may not fit them.)

Give time and encouragement, but do not make the balance for any child, unless he is handicapped. (If it does become necessary to make the balance for a child, the teacher should carelessly take away with him the straw that he has pierced and adjusted, leaving the child to make his own. Otherwise, the sense of doing one's own experiment gets lost.)

A child who does not get his balance made may do without, or he may take it home to finish it. A child who does get his balance made may certainly take it home.

CHAPTER 3

Rough measurement

'Or how to guess sensibly'

Metric units are used throughout the course; so we take several opportunities here and elsewhere for class experiments that give practice in using and in estimating with these units. Carrying such measurements down to atomic sizes enables us to show how scientists sometimes value rough estimates and we encourage children to make 'scientific guesses' (and later on to judge their reliability). A scientist is a sort of detective, who not only finds clues but spends a lot of thought trying to build knowledge from his clues.

Measuring small things with instruments such as vernier calipers or a micrometer gauge involves nice instruments but takes up more time, without great interest, than seems worth while in this course. And with young pupils that may give science a mistaken reputation. So our measurements of length are rough – to be made more precise much later, if needed.

24 Class Experiment

Measuring the thickness of a penny

APPARATUS *item no.*

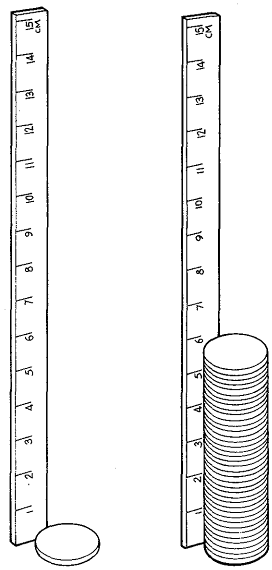
Large supply of pennies

32 Rules with graduations in mm *(metre rules, item 501, will suffice)*

PROCEDURE

Ask children to measure the thickness of a penny. This will raise a problem for thinking, and will provide a useful method for later use. Each child should try to measure the thickness with a ruler that has millimetres (not inch fractions) marked on it. The teacher should ask for results and ask how reliable children think they are. Then ask for suggestions for improvement. Here, as often in this year, it is worth while to wait a long time for the suggestion to come from children themselves. Some will suggest measuring a pile of pennies. We should praise that as an idea and ask them to carry that out as an experiment.

After that, we might discuss the general idea of accuracy behind that method:



Suppose you have just one good penny and this ruler marked with millimetres, how thick would you find the penny if you could measure very carefully? . . . Yes, we do know that the thickness is 1.5 millimetres, but could you really see that if you had just *one* penny to measure? Even if you thought you could see it, would that be a safe and fair answer to give? . . . With just one penny what would be the fairest thing to say? . . . If you wanted to be quite safe what would you say? . . . Yes, I agree; all we can say is somewhere between 1 and 2 millimetres.

Now suppose you have 10 pennies in a pile and measure the pile. Even if you make a mistake of one millimetre in that, how much of a mistake is that in the thickness of one penny? . . . So if you measure 10 pennies you could say that you think each penny is 1.5 millimetres thick. What could you say if you measured 100 pennies in a pile?

Leave the problem at this point. Big numbers and small decimals are not easy, and the problem of accuracy is not a particularly interesting one yet.

If the matter of worn pennies being thinner than new ones crops up, it might be worth while to sort them out according to the picture on the heads face and make a rapid comparison of piles. Of course this kind of experiment is of far greater value if children suggest it themselves, or even if the teacher can coax it out of them in a way that makes them feel it is their own suggestion. Then they are doing science.

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25 Class Experiment

Measuring the thickness of a sheet of paper

APPARATUS *item no.*

6 Large packets of paper each containing a known number of sheets (e.g. 500) (books may also be used)
32 Sheets of the same paper
32 Rules with mm graduations (*metre rules, item 501, will suffice*)

PROCEDURE

Next question: 'What is the thickness of your paper?' Ask for suggestions. The pennies experiment should help. The large pile of paper that was there in connection with the microbalance weights is still there. The teacher should point to that and ask if that would help. Children should make a rough measurement of the thickness of a pile or a book and calculate the thickness of a sheet and record it in their notebooks.

Some children will read page numbers and forget that there are two pages to a sheet. That mistake is better avoided at this stage; so the teacher should issue a reminder.

A problem on atoms

Give the children a very rough value for the size of an atom and ask how many atoms thick that paper is. For paper made of cellulose, containing carbon, hydrogen, and oxygen, the average atom diameter is probably only about $\frac{1.5}{100\,000\,000}$ of a centimetre. Of course paper has a good deal of open space among the fibres; so one can make only a very rough guess.

Here, as elsewhere at these early stages, children who find calculations with these huge numbers difficult or unpleasant should not be dragged through repeated attempts to get them right. They should be encouraged to wait until later, the teacher pointing out, quite honestly, that the world will not end if one is unable to work out how many atoms there are in the thickness of a sheet of paper.

It's only fun if you find you can do it. Wait, and you will be able to do it quite easily presently, if you stop worrying.

26 Class Experiment

Measuring the thickness of aluminium leaf

(Optional)

APPARATUS *item no.*

8 Books of aluminium leaf *10G*
16 Plastic measuring rules *25*
32 Microbalances *4*

Each pupil will need two pieces of aluminium leaf, each 5 cm^2.
The microbalance should be the pupil's own balance made in Experiment 22. He will also require the microbalance weights made in Experiment 23.

PROCEDURE

Show a piece of aluminium leaf (this will be used anyway for radiation experiments later) and ask:

How could you find how thick this is? It's the thinnest sheet of aluminium that you can get, beaten out till it's so thin that it flutters in air, and you can almost see through it. I wish I knew how thick it is.

This will lead back to the microbalance.

The teacher will probably have to give help with calculations this time. Here is a case where considerable help is a good thing, so that this 'theoretical' investigation succeeds quickly. A skilful teacher will coax the pupils through the calculation without their noticing that they are not doing it themselves. (And when he gets the answer, he will mutter under his breath, 'Atoms must be a lot thinner still.')

If the aluminium leaf is used like this, promise that it will be used again later in the year in an experiment with radioactive atoms. Then when the spark counter for alpha-particles is shown at the end of this year, put a piece of ordinary paper between the source and the counter, then replace it with a piece of this aluminium leaf: and you will be able to say:

The paper stops the alpha-particles and the leaf does not stop them. There are so many atoms in the thickness of paper that the alpha-particles are brought to rest by collisions. But in the thin metal leaf there are not enough: the alpha-particles smash their way through.

Metric measurements

Unless the children are already familiar with the kilogram and gram, metre, centimetre and millimetre, so that they have some feeling for the sizes of those units, we should give them practice with them in some simple jobs of measurement. These can be done any time in this year, early or late, preferably in small doses as an interesting game.

a. Measure the length of this sheet of paper in centimetres, metres. Write in your notebook:

length of sheet of paper . . . xxxx centimetres
length of sheet of paper . . . yyyy metres

b. Measure your own height in centimetres and in metres and write the values down.

c. (*Optional* – suggested only for a fast group.) Give children a number of small pencil leads or needles or nails, etc., and ask:

How thick is one of these? First just guess. Is it a metre? A centimetre? A millimetre? Half a millimetre? A tenth of a millimetre? Now have a look with it on your ruler and guess again. But even that's a fairly rough guess. How could you find the width and be fairly sure you are right, without using any special instruments?

The teacher should wait for suggestions and discuss.

For many children guessing the sizes of things in centimetres and millimetres and metres is both a good way of getting used to the metric scale and a valuable introduction to rough measurement. It is good modern science teaching to encourage some rough measurements and estimates as well as precise ones.

(This is *not* the time to bring in a micrometer gauge. That is perhaps a special reward for a child who is farther ahead and can be left to find out how it works with relatively little help and will treasure it as special knowledge. Only much later in an engineering workshop will grown-up children find they need to use that gauge; and then it is surprising how quickly the young apprentice, who wants his future job, can learn. As a delightful instrument that is a reward for a few, the screw-gauge is excellent; but, as discipline for all, it takes too much time – of which too big a fraction is repeated explanation by the teacher – and does not lead to an obvious important use like the skilful part it plays in a workshop.)

Discussion: rough measurements To many children the image of science is one of exactness and perfection. And yet, good scientists make a rough estimate again and again, sometimes without any precise measurement. We must teach children that rough measurements are respectable.

Of course high precision is of the essence in many cases. A modern mass spectrograph must yield measurements of high precision if the tiny mass-differences between one atomic nucleus and another are to be interpreted as energy-differences using $E = Mc^2$.

Yet, when Chadwick measured the nuclear charges of copper, silver, and platinum by alpha-particle scattering, relatively rough measurements could prove the case that was suspected in Rutherford's great atomic model. He showed that the nuclear charge (in electron units) is just equal to the 'atomic number', the number of the element in the complete chemical series arranged in order of atomic weights. Those answers were suspected from the general pattern of theory, and had to be whole numbers since the complete atom of [nucleus + outside electrons] is neutral. Much more precise measurements were neither needed nor, at that time, possible.

Even before that, the first hint of atomic number measurements came from Barkla's attempt to measure the number of electrons in a carbon atom by the scattering of X-rays. His measurements suggested a number about 6 electrons per atom, more honestly somewhere between 5 and 7; yet this rough estimate enabled the founding of atomic theory to proceed.

Galileo made the roughest measurements for his test of constant acceleration down an incline – he knew he was right in his simple summary of natural behaviour. He just wanted to convince some people by quoting an experiment.

Rough estimates are not just 'a misfortune peculiar to early, clumsy experimenters': they are the right thing in some parts of growing science. Nuclear physicists and modern cosmic-ray investigators make some very precise measurements; but in other cases they seek only a rough estimate to settle an essential point.

We cannot give that explanation to children, because it refers to physics that is quite unfamiliar; but we should, from this very first year, give them examples of the rightness of rough estimates in cases which we can call 'scientific':

An invading army is about to go into a foreign land and the general wants to know the size of the enemy's forces. From spies he learns they are about 18 000. Does it matter much to his plans if there are really 19 000 or 15 000? What he wants to know is that there are about 18 000 and not, say, 30 000. If he waits while the spies and his army staff carefully sift the reports and add up the guesses and check them and find that the enemy really has 18 473 men, the general will start out too late to win the battle.

In a city where a big snowfall has to be cleared from time to time in winter, the example of the man in charge who makes the decision about snowploughs and clearing-men in the middle of the night is a good one. The Chancellor of the

Exchequer makes a clever guess of the total consumption of tobacco. A rough guess that the Sun is 300 000 times as massive as the Earth suffices to tell us that the Earth is too light to affect the orbit of the planet Venus at all noticeably in any ordinary astronomy; and in modern studies of high precision, that rough estimate is still sufficient to give us the small effect that is noticeable. A rough guess at our distance from a measured radioactive source is sufficient to tell us what we need to know about safety.

We need to make children familiar with the idea that such rough estimates are a good part of science before they meet the measurement of the size of an oil molecule later this year, or they will lose the delight in it by being shocked at its roughness.

27 Class Experiment

Guessing lengths, times, and weights

APPARATUS *item no.*

1 Metre rule *501*
1 Stop-clock or stop-watch *507*
1 Measuring tape (optional)
16 1-kg weights *32*
16 100-g weights *31/2*
1 Balance *42*

PROCEDURE

Hold a book up (vertically, to avoid foreshortening for children out at the side) and ask for a quick guess of its height, in centimetres. Ask the children to write it down on a piece of rough paper; then hold a ruler beside the book.

Repeat with a finger breadth, the length of the room, an odd bit of stick, then a book again, etc., asking for quick guesses and checking them visibly at once – not collecting scores or having marks, but promising to go on with this in the next lesson. This will prove to be a skill that can be polished up with great success, though it does not seem to last for many months.

The same kind of thing can be done with intervals of time. Ask, 'How long in seconds between these two hand-claps?' Then, 'How long ago did I drop that book?'

For weighing, try guessing by feeling a book and other objects with weights between say, 30 and 600 g, in grams and in kilograms. 'How much do you weigh in kilograms?' For that, we must hand out specimen metric weights to each pupil: one kilogram, one hundred grams, ten grams, and if possible one gram. Most pupils find weight-guessing much harder than length-guessing. Yet we should ask for it – and encourage success by giving praise – because we want to build a familiar acquaintance with grams and kilograms.

Show a litre: guess volumes in litres. Ask for a guess of the weight of a litre of water.

All this weighing and measuring should be done quickly and lightly, without making much of a record and without doing any calculations. It is just to gain facility, particularly with metric units.

Private note to teachers: discussion of the word 'weigh' The verb 'to weigh' and the noun 'weight' are used in such conflicting ways, even in science, that we can never clear up the great distinction between mass and weight by narrowing down the use of those words – and they are so common that we cannot hope to exclude them or replace them in science. So, both we and children will have to live with their sloppy complexity.

Therefore at this stage we just use 'weigh it' to mean 'put it on the balance and see what the balance says' and we do not raise any question of mass versus weight unless someone asks clearly, 'What is the *name* of the number that we get?' Then the best answer is MASS – with a promise of explanation later.

Even that is not very helpful, because what our balance feels (and what I feel if I put the object on my hand) is a force that arises from the pull of gravity on the object; and we should call that force the object's WEIGHT. With such a balance we are comparing the weight of one object with the weight of some other standard thing – a standard kilogram, or the weight of the counterpoise on the modern weighing machine – and that comparison will give the same ratio if we transport the whole experiment to the Moon or anywhere else where there is enough gravitational field to make the machine work at all.

Whatever teachers decide to do about the distinction between mass and weight, it is important that they should never be guilty of shoddy thought or expression: the pupil should insensibly acquire the right idea by their care in its use. Actually, the distinction between mass and weight comes fairly easily to some children in this 'space age'; so teachers should be prepared to make a short general comment if a good occasion arises. However, there should be no strong insistent teaching or written notes to try to keep the matter straight because both, at this stage, may store up discouragement for later ages.

28a Class Experiment
Timing things

APPARATUS *item no.*
16 Stop-watches or clocks *507*
or
1 Large wall clock with seconds hand
Several metre rules *501*

Where the laboratory has enough stop-watches or clocks for class experiments, pupils can work in pairs and make some quick measurements of time in seconds, just to gain familiarity with the instrument. Alternatively, a large wall or demonstration clock with a sweep seconds hand can be used.

PROCEDURE

Invent some real jobs for this practice: the time taken by a boy to walk or to run ten lengths of a room and to measure his speed; the time taken by another pupil to run up a flight of stairs (with a promise of calculating power later on); the time taken by a ball to fall 1 m, 3 m, from rest.

28b Class Experiment
Using a broom-stick to measure time

APPARATUS *item no.*
1 Broom handle *10F*
1 Wooden platform *10F*
2 Nails (15 cm)
4 Bricks
2 Cross-beams of wood
Laboratory stools

The basic parts for the heavy pendulum are included in the Year 1 general kit (item 10F), they are of course easily improvised as there is nothing special about them.

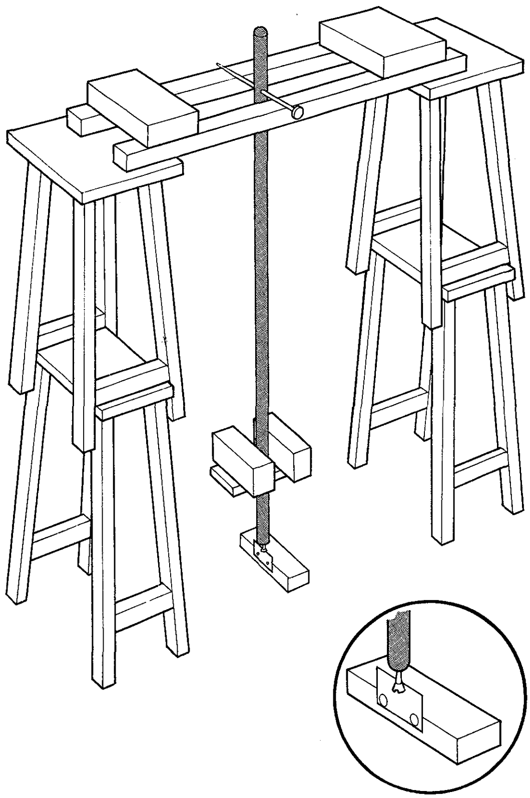
CONSTRUCTION

A broom handle is drilled about 3 cm from the end to take a nail about 15 cm long.

A wooden platform about 20 × 8 × 2 cm, with a hole in it to take the broom handle, is pushed over the handle and is secured in place by a second nail pushed through a hole drilled in the lower end of the handle. This second hole should be about 110 cm below the top hole.

A 25-mm round-headed screw is then screwed into the bottom of the broom handle so that the head projects about 12 mm.

A suitable number of laboratory stools is erected on the bench. Two lengths of wood (not provided, but 5 × 5 cm would be ideal) are placed horizontally across the stools. (Bricks resting on



the ends will hold them rigid.) The pendulum is supported from these wood lengths, the nail will roll on them. When stable, the pendulum platform is loaded with two bricks which can be tied into place.

A piece of thin card about 8 × 4 cm is fastened to a small block of wood (about 6 × 4 × 12 cm) and positioned so that, in swinging through the mid-position, the screw head which protrudes from the pendulum bob strikes the broad side of the card, making an audible click.

NOTES

1. A rigid pendulum of this type has a period of about two seconds so that the audible clicks occur at about one-second intervals.
2. Rigidity is essential, otherwise there will be an unnecessary loss of energy.

3. If the pendulum does not make enough swings, add more bricks to the platform.
4. It is worth noting that the period of the pendulum will not be altered when the bob strikes the thin card provided the card is placed so that the contact occurs in the mid-position.
5. The sound can be reinforced by sticking the card to part of a balloon, which is stretched tight and tied over the top of a 1000-cm^3 beaker.

USE

This crude clock can also be used for the timing work described above. It is good to know that lack of beautiful shiny apparatus need not stop progress in science – and where apparatus for modern physics is needed and expensive, an economy like this may be wise.

The crude brick pendulum hits a card as it passes through the lowest point each time to give audible signals. The piece of card that is to mark the swings audibly must be placed so that the pendulum hits it sharply and does not slide along its surface. Thus, the card must be perpendicular to the plane of swing. Simple schemes for mounting the card on a beaker or even on a rubber drum to increase the sound may be tried. If there is a great deal of background noise, the pendulum may be arranged to hit a small bell. The hits which signal the time will, of course, make the amplitude of the pendulum decrease fairly rapidly. However, that will not change the timing appreciably, so we let the amplitude die down without worrying. Since the impacts which lessen the motion occur at the mid-point of the swing, the *phase* of the motion is not changed in that abrupt decrease of motion. Thus the pendulum continues to keep its true period. Or one child watching the pendulum can make estimates from signals given by the others, to a fraction of a swing. Those of us who have tried it say that children enjoy the ingenuity of this scheme and find it less clumsy and more satisfying than adults do.

Note that this pendulum is intended only as a simple timing device, at this stage. It should not be used for an investigation of the properties of pendulums. We hope pupils will take it for granted, and perhaps not even raise the question of the decreasing swings taking the same amount of time. If they do, the teacher should say, 'Shut your eyes and listen'.

A demand for more precision can then produce willing volunteers to try things with wrist watches and magnifying glasses; and presently we shall find the BBC providing time signals for school laboratories.

Note on statistics Statistical treatment plays very important parts in modern science. In advanced experiments we expect to treat errors with some statistical care. In kinetic theory we recognize the steady pressure of a gas as an average of innumerable individual bombardments, but we need statistical help before we can delve into details of molecular speeds or sizes. And in modern atomic physics, statistical views are of prime importance. So we might well make a gentle start now, by showing how we look at a number of measurements of the same thing.

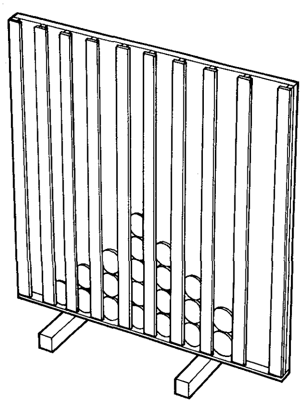
We should not give special lessons on statistics – certainly not at this stage in science – but we should take opportunities to make informal beginnings. Both in experiments described earlier and in some experiments to come later, we should collect and exhibit statistics.

28c Class Experiment
Introduction to statistics *(Optional)*

APPARATUS *item no.*

1 Statistics frame *48*

This frame is provided with slots to receive counters to form a demonstration histogram. When using it, it is important to explain that each vertical slot corresponds to an agreed range of whatever is being catalogued – in the case of pupils' weights, one slot might take weights in the range 40 to 44.5 kg, for example.



PROCEDURE

When every child knows his own mass in kilograms, make a one-dimensional 'graph' by drawing a line marked in kilograms with a mark on it for each child's mass. (If masses are not known, use height instead.) Include the origin on that graph, and then when all the marks cluster in one region far from the origin, offer to make an 'exploded graph' of that region. Do not make any calculations of average or deviations, but just leave the 'graph' there for people to look at.

If you like, do the same thing for everybody's weighing of one single block of some material: in that case, the graph exhibits errors rather than the natural spread of some quantity. Make a 'histogram' of crosses on a blackboard; or make it with a frame for columns of pennies.

Make a similar 'graph' for the results of class experiments on weighing and measuring blocks of some one material and finding the density. Perhaps make a 'graph' for weighing ten grains of sand.

At this stage, the only question we should raise is one concerning the meaning of the average value and reliability of our estimate of it, with no technical discussion of statistics and errors. This is a good example of something we should do as a matter of general policy: glance at important aspects of scientific work as we pass by them, much as a family in a train may point out animals to children as the train goes by, without any question of stopping the train and getting out to do zoology. These casual looks and comments, if made with the tone of one adult talking to another, are good teaching, reminiscent of the way in which a much younger child builds its vocabulary.

In discussing their work with pupils we should help them to assess the value of their results and to discard unnecessary figures. Here again, we do not analyse and labour the point, but indicate it casually every time the occasion arises. Rough estimates of the magnitudes of physical quantities should be called for frequently in the work, and critical judgements of what is reasonable both in observations and results obtained from them. The theory of errors should not be a startling piece of news in the sixth form. It should be the formulation of a commonsense attitude acquired gradually over the previous years.

Fermi questions To encourage children to develop the useful skill of guessing, the *Pupils' Text* offers a number of simple 'Fermi questions' at this point (see *General Introduction*, p. 44).

CHAPTER 4

Balancing a seesaw

'Or how to look for a law'

Two sets of class experiments in this and the succeeding chapter give opportunities for children to work at their own pace and find out as much as they can. This one is an 'open' experiment with a simple lever. 'Find out what you can about arrangements of loads for balancing' is the instruction. We do not expect many children to arrive at a formal rule of moments. Our chief aim is to provide a field for their own experimenting; and we want experimenting to encourage some reasoning within the child's compass.

29a Class Experiment

Balancing the seesaw: an open experiment leading towards the lever law

APPARATUS *item no.*

16 Wooden beams *5A*
16 Triangular fulcrums *5B*
Special 'square pennies' *5C*

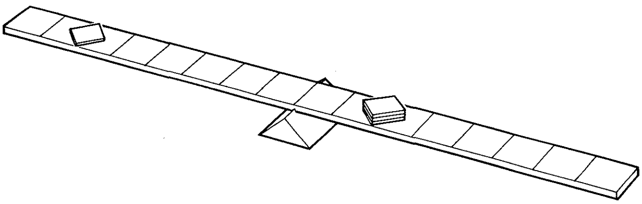
There should be one beam for every two pupils.

PROCEDURE

We offer a very simple form of seesaw, for experiments on balancing loads. It should be simple and robust so that we can encourage experimenting without saying much about what to look for. Pupils follow these instructions:

* * * * *

Here is a seesaw. Balance it on the wedge at the centre. Put some loads on each side. You should put the loads at the marks so that you know when a load is one step out or two steps out or four steps out from the centre. Avoid putting a load $2\frac{3}{4}$ steps



out because that would make it harder to find out the scientific story of seesaws. First make the seesaw balance with two piles of pennies, one each side.

When you have it balanced, the seesaw will tip over to one side and stay there, and it will tip over to the other side and stay there. You will not be able to make it stay exactly balanced in mid-air. That is because it is sitting on top of the support at the centre, ready to fall over either way. But this will be just like 'weighing sweets', when the scales are exactly balanced and you find ever so little more would tip the scale one way or the other.

You have balanced the seesaw with two piles of pennies. How can you move the pennies and keep the balance?

Find out what you can about balancing a seesaw, with different loads on it. Make notes in your notebook of what happens. Try any arrangements you like. See if you can find out some rule or story that you could tell to other people about balancing loads.

* * * * *

Some children will find the simple 'lever law' for unequal loads balanced on a seesaw. Others will go far in working with several loads.

The lever law may seem to us an obvious, simple, rule; but if we can give each child a simple seesaw to play with, the class will make delightful and useful discoveries – one of which is essential to our later discussion of energy.

Every child (or every two, for economy) should have his own seesaw and set of equal loads, with a fulcrum on which to balance the seesaw. We suggest the seesaw should be a thin lath of wood about 60 cm long, marked with a pencil line across every 4 cm from the centre line, the loads should be small squares of metal; or pennies can be used. We suggest using square counters of metal, 'square pennies', because they can be placed easily and fairly accurately on one of the pencil marks, with their diagonal on it. (Most children will need a suggestion of this placing.)

NOTE

Told what to do, children can do the simple version quickly; and, led into formulating rules of moments, they can proceed to complicated arrangements quickly; but that would lose the whole point of this experimenting – working as a scientist oneself and finding one's way into knowledge. Left to themselves, some children will find few things, others many. Encouragement is needed to prevent the quicker ones being bored or the slower ones getting muddled.

The object of this experiment is not to get the children to deduce a proper 'rule of moments'; nor to proceed through a series of increasingly difficult arrangements to a steelyard; it is meant to provide a simple investigation for children to carry out on their own, each finding what rules he can. Above all it is meant to remain in the children's hands and not to lead to a formal discussion of moments.

The apparatus should be so designed that it is difficult for pupils to lose themselves in useless precision and excessive numerical manipulation. We are most anxious to avoid this experiment becoming complicated and leading in quite a different direction through the use of more sophisticated apparatus. A metre rule, with centimetres and millimetres on it, will lead to a distracting preoccupation with precision and arithmetic. A beam with special holes at appropriate points, or clamps for a movable axle, will tempt our teaching away from the present aim – towards discussions of centre of gravity, design of steelyards, and formulation of rules of moments which would be discouraging.

We want children to look for a simple rule with such simple apparatus that they will find things out for themselves. This experiment must have simple equipment, pupils should find it just like the ordinary ruler and pennies that we hope some of them will use for experiments at home. Therefore we shall give a detailed discussion of the theory and design of the equipment we suggest.

Encourage the children to find a rule that covers all the cases they have investigated, but leave them to do it themselves, follow false tracks, and find other rules too. This type of experiment is worth several class periods because it encourages a deliberate and conscious effort to formulate a law of behaviour – a process which is fundamental to science, and used continually but unconsciously in everyday life.

The simple commutative rule will certainly emerge, that three pennies two spaces out will balance two pennies three spaces out on the seesaw, and that is all that we need for our discussion of energy. Faster pupils will work with several loads on each side of the seesaw and may discover a rule of moments. The teacher should *not* dictate that rule, or even coax it out – that would give quick physics but a poor view of how science is done. (We should not give the name 'moment'; and we should not embark on discussion of clockwise and anti-clockwise turning effects. That is good physics, but these are young pupils who should be working on an interesting, empirical experiment. Even after the experiment, we should not discuss the moments type of rule in detail for any except a fast group who seem to ask for it.

The teacher should encourage the children to make a record of many different arrangements that do balance: and then coax them into looking for some rule that fits those cases that they have.

For the notebook, very simple things will suffice. Note-taking should not delay the experimenting. Labelled sketches – such as many a good scientist uses – can well replace words in notes.

Remember that finding a systematic rule, finding a constancy in Nature, is both what scientists have to do for their growing knowledge of Nature and what children do in an informal unconscious way when they first begin to ask about the material world. They codify it in the form of simple statements about what is natural, such as 'grass is always green'. Although they employ this process of looking for general rules of behaviour unconsciously, it is an unfamiliar one to children, not an obvious need. Therefore, looking for a law or rule needs coaxing and praise; and failure should not be condemned or safeguarded by a helpful announcement at this stage.

Some children will find a moments rule of products with delight, others will find an 'additive rule': since they are using equal blocks or pennies, they can take the distance out from the fulcrum to each block and add all those distances to obtain equal totals for both sides of the seesaw. This 'addition syndrome', as one group of investigators called it, may seem unfortunate, but it is probably best left for later revision.

Some children who 'know the answer' to the simple form of the problem will not want to try this lever investigation; but others will enjoy seeing it actually work. The former group should be dared into trying more complicated schemes with several loads on each side and may even be faced with the problem-game of Sym (see Experiment 30a below).

An open experiment The essence of this lever experiment is open-ended play to find out all one can; and if it spreads over three or four class periods, we can be quite sure it will be much more valuable than if it gets finished in one. Like the microbalance, this is a case where the teacher will have a much happier time in the second round of teaching – he is likely to encourage the experiment to spread over a longer time in that second year.

For very fast students there are problems like the steelyard, and the idea of centre of gravity will make itself felt; and the name 'moment' may prove to be a label for a useful quantity; but with slower children, beware of giving a name which will take charge and overburden the experiment – remember Freud's warning: 'Words and magic were in the beginning one and the same thing.'

Notes
on the design of the simple seesaw apparatus

This seesaw must be sensitive enough to make it easy for children to see the relationships; so the lath must not be so thick or so heavy that its weight has enough moment to compete successfully with a small misplacing of a load.

Therefore we wish to avoid the traditional form of 'law of moments' equipment in which weights are hung carefully on a long bar graduated in millimetres, careful measurements are made, and moments are calculated following specific instructions. Far from that, we wish the apparatus to look simple and, if possible, to ask its own question. Therefore we have chosen a plain lath of plywood, balanced on a small wedge of wood. The balancing point should be at the middle of the lath.

There should be no sign of alternative places for the fulcrum, which would lead to complications over the centre of gravity by bringing in the weight of the lath itself. The balancing at the centre should be done by placing the lath on the supporting fulcrum, rather than using a specially drilled hole. That is because we wish to keep the apparatus so simple that similar experiments could be done with rulers at home. But to make the start of the experiment easier, we do advocate making a shallow notch across the lath, where it rests on the fulcrum. That will weaken the lath somewhat, but we believe pupils will treat it carefully when they are using it for an interesting experiment – and anyway the laths can be replaced quite cheaply from any supply of plywood.

The loads The loads to be placed on the lath should look simple and identical. In fact they must all weigh almost exactly the same, or pupils will have considerable trouble. It is not easy to provide a large number of loads that are all equal in weight within, say, 1 per cent – which is the tolerance we consider necessary for simplicity and success in this experiment. Even new pennies from the bank will usually fail to meet this requirement. Squares of brass chopped from standard strip will deviate from an average weight more than we want. So the providing of suitable loads has raised serious problems. However, it is hoped that laboratory suppliers will be able to provide suitable objects. This may seem to teachers a serious breach of our own strong principle that materials and equipment for our early teaching should be common and familiar, rather than special devices manufactured for teaching. However, in this case the provision of 'square pennies' will give this experiment tremendous help – help that it needs, since we want pupils to extract a simple result from it.

Adjusting square pennies to uniform weight In our preliminary trials, schools were provided with square pennies chopped from brass strip, 1 inch wide by $\frac{1}{16}$ inch thick (i.e. about 25 by 1.5 mm). They were not sufficiently uniform in weight for this experiment. In fact, they varied so widely that they spoiled the experiment for some classes.

However, we can now suggest a cure, for use in those schools who already have such square pennies, and others who wish to make them inexpensively: sort the pennies into groups by weight, then drill an appropriate hole through all the pennies except the lightest group. It is far easier to achieve 1 per cent precision than one would expect. The area of a square brass penny is, say, 625 mm^2. Suppose we drill a 4 mm diameter hole through it. We shall reduce its area, and its weight, by 2 per cent. Making the hole $\frac{1}{2}$ mm smaller reduces this to just over 1 per cent. If a range of $\frac{1}{2}$ mm drills is available, trial and error will soon find the drill to be used for each group of pennies to bring them all to within 1 per cent of the lightest.

Placing the loads Placing blank pennies, singly or several in a pile, on the lath, will lead to a great variety of distance measurements which will obscure the story, unless we give a strong hint in the form of a crude scale of steps marked along the lath. Therefore the lath should be marked with strong pencil lines regularly spaced, as a hint of places where pennies should be piled.

We ourselves would find it easy to place a round penny on a ruled crossline so that it appears to be centred on the line. But young pupils may not find it so easy to make that judgement, which we do by symmetry. Therefore it may be helpful to have 'square pennies' because a square penny can be placed on the ruled lines with its diagonal on the line. We should suggest this trick to pupils. (This is not the point at which we should wait for them to think of it. They have graver matters of physical investigation in mind.)

Unstable beam intentional With square pennies piled on marks on the lath, pupils will be able to find arrangements which balance. However, *this loaded lath is essentially unstable*. Teachers who have used it in trials have reported considerable dismay from both pupils and the teacher himself, when the lath failed to remain poised when the right loads had been placed on it for balance, but tipped over either way.

This led to suggestions of alternative models which would be stable. But the latter are both less sensitive and in most cases more complicated. In fact the business of building a seesaw which is stable and sensitive is the prime problem of the design and manufacture of a good chemical balance. As long as we seek simplicity with some sensitivity, we shall encounter instability.

However, we can avoid dismay if we *start the teaching with a clear statement to pupils*:

'This little seesaw which you are going to use will tip over to one side and stay there if you put too much load on that side. When you have it balanced it will not just stay level but will tip over to either side and stay there. That is because of the way it is supported with the wood block underneath.

'So you must do your weighing "LIKE WEIGHING SWEETS". Put whatever loads you want on one side and then go on putting loads on the other side until the seesaw just tips over. Make sure it is only just tipped over, *so that it will also tip the other way*. That will be like weighing sweets, and making quite sure you are weighing them as fairly as you can.'

That description 'like weighing sweets' will assure pupils that the unstable arrangement is something we know about and are going to use. Teachers who try that in an 'open experiment' with pupils will find that the worries about instability do not arise seriously and the pupils are able to concentrate on the main job of looking for a lever law.

29b Class Experiment
Using the law

APPARATUS *item no.*

1 Wooden plank (about 2 m long, at least 20 cm wide and 2.5 cm or more thick)
1 Brick or wood block, as fulcrum
1 Metre rule *501*
16 1-kg weights *32*

The wooden plank is not provided; it is assumed the teacher can find one.

PROCEDURE

A demonstration seesaw 2 m or even 4 m long using bricks as loads is worth having now; and it gives the chance to weigh a pupil: balance the beam at its mid-point on a large fulcrum on the floor, let the pupil stand 20 cm out from the fulcrum or sit 40 cm out, and balance again by adding kilograms far out on the other side. A useful suggestion from a teacher in trials: let pairs of pupils weigh each other, as an application of the lever law, *as soon as they have discovered the law*. This is likely to be a very successful 'carrot' to speed up the investigation.

Steelyard. For a very fast pupil or one with special interests, we may suggest an investigation of the steelyard. No special apparatus is provided for that, but the pupil may use a metre stick or dowel of wood hung by a loop of string, carrying loads on loops of string.

The lever experiment, which teachers will expand after once trying it, leads to a discussion of machines and energy later in the year, and it throws light on weighing-balances straight away. For the latter reason, some teachers will be tempted to place it much earlier in the year to precede weighing with balances, but we advise others not to worry about logical order; we think it better to use the balances first and then to illuminate them.

30a Class Experiment
The game of Sym

This game was devised by a mathematical physicist, and can be absurdly simple or extremely hard.

In the following description the unit loads are called pennies and the beam is supposed to be balanced at its centre and marked off in equal steps out from the centre each way. Pennies are supposed to be placed on these marks and never at any intermediate places.

Instructions Start with the beam balanced with no pennies on it. Take several pennies and arrange them on the balance (at marks) so that the beam is again balanced. Make a note (e.g. by a sketch) of that pattern. The game is to find the smallest number of moves to arrive at that balanced pattern of pennies, starting with all those pennies in a pile at the centre point. A move consists of moving two pennies and no more; and the beam must be balanced before and after the move.

The teacher needs to demonstrate the game first to would-be competitors, starting with a very simple pattern, so that the rule about moves is clear and the object of the game – to find the smallest number of moves – is also clear. Then it goes very well indeed provided one has some way of putting the brakes on fast children so that they do not discourage slower ones.

30b Class Experiment
A simpler game

Instead of Sym, some pupils enjoy a simpler game in pairs; one pupil places pennies in some pattern on the marks on one side, then the other pupil has to find where to put two pennies to balance.

CHAPTER 5

Investigating springs

Finding a law for stretching (and squeezing)

The pupils go on to an experiment with an even wider variety of possibilities: investigating a spiral spring. Again, we give apparatus, time and encouragement; with both praise and some constructive criticism afterwards. But we do not give detailed instructions. Nor do we help children by doing their experiment for them. In these 'open' experiments they should find the pleasure of some success and meet some of the difficulties that beset professional experimenters. The springs experiment is a simple fruitful experiment. For all children, the spring holds a law to be discovered – and exceeded, because real children go bravely on beyond the elastic limit. (It is only the pupil who has been too thoroughly trained that wants to stop when his spring 'goes wrong'.) But, for most children, there are many more things to find out about springs – given time and given plenty of springs. We must remember that doing experiments in a laboratory – using apparatus – is strange to our pupils; they will find delight in what is only too familiar to us.

31 Class Experiment

Making a spring

APPARATUS *item no.*

8 50-g reels 26 SWG bare copper wire *2C*
32 Retort stands *503–504*
32 Bosses *505*
32 Nails (about 12 cm long) *10H*
16 Weight hangers with slotted weights (10 g) *31/1*
16 Metre rules *501*

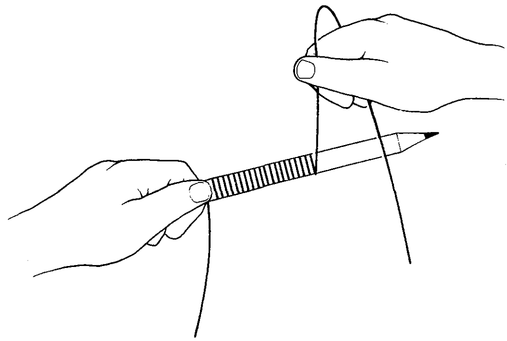
PROCEDURE

Pupils follow these instructions:

* * * * *

Make a spring, and hang things on it, and find out how it stretches. Here is some copper wire that you can wind on a pencil to make a spring.

* * * * *

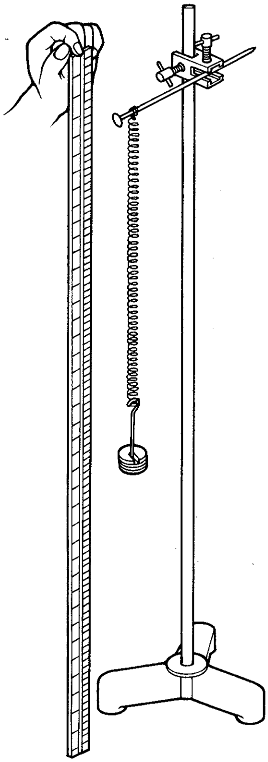


We must provide new copper wire for this for two reasons: (1) old wire is often uneven in its hardness, because the use of copper wire work-hardens it; (2) when one winds wire on a pencil in the ordinary way, one puts an extra twist in at every turn, and that will lead to an uneven spring if it is done with old wire that already has twists.

(Teachers who are familiar with the latter difficulty may feel tempted to avoid it by showing children how to wind a spring by turning the pencil instead of winding the wire round and round it by hand, so that that extra twist is avoided. But that seems an unwise thing at this early stage. We want children to make springs quickly and then enjoy trying them.)

Since the whole point of this experiment is to provide personal experience, it is a serious disadvantage if pupils have to work in pairs, one watching the experimenting being done by the other, or prolonging the time by having to take turns. Other experiments may be good practice in co-operative work, but this one belongs to each child on his own. Therefore we urge teachers to provide enough apparatus for each child to have his own spring and make his own experiment on it. That will demand a plentiful supply of copper wire, and later of steel springs, but those are cheap. It will also require one retort stand and boss head and rod of wood or metal for each child. We regard that as essential 'kitchen equipment' for any good laboratory that is following our programme. Such a full set of stands is needed now and will be absolutely essential when children come to the oil-drop experiment.

Give each child a firm retort stand with a projecting rod from which to hang his spring, and – as an obvious hint – a set of equal loads, such as slotted weights on a hanger, or equal weights with hooks.



Let the children stretch their springs and overstretch them. When they ask what to do with a ruined spring, we can say, 'Can you put it back to the shape you started with? Or would you like some fresh wire?'

This should not take long, because we ask for no notes to be taken; but yet we should not hurry it for those children who enjoy doing this for the first time and want to repeat it. We bring it to a close not by saying that it's time to stop, but by announcing a tempting offer of better springs made of steel wire.

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32 Class Experiment
Steel springs

APPARATUS *item no.*

Expendable steel springs *2A*
32 Retort stands *503–504*
32 Bosses *505*
32 Nails (12 cm) *10*
16 Metre rules *501*
16 Weight hangers with slotted weights (100 g) *31/2*

The pupils should work in pairs, but there must be plenty of spare springs as they will be stretched beyond their elastic limit and replacements will be necessary.

PREPARATION

These simple steel-wire springs are rather dangerous to wind on a lathe. The wire uncoils suddenly when one releases it, and can make serious gashes. Special 'springs-for-Hooke's-law' may be expensive to buy from apparatus-suppliers, and we certainly should not spend money on them. It is cheap and easy to get simple, steel-wire springs from spring manufacturers. The makers will supply springs ready wound, cut in short lengths of 2 dozen turns, probably with coils pulled close together in contact. A suitable spring has coils of diameter about 15 mm – narrower coils will make the behaviour and observations more difficult in the later stages – wound of piano wire of such gauge that a spring of 2 dozen turns stretches about 5 centimetres for 100 g of added load.

If one asks the makers to turn up the last two coils at each end and add solder to make a strong loop, that will make the springs more expensive. (However, in our Nuffield trial we asked the suppliers to do that, to lessen the burden on teachers busy trying out our programme. Since each class uses a large number of springs this preliminary soldering by the suppliers saves teachers a considerable amount of work. Furthermore, it encourages a general feeling in the laboratory that there are plenty of springs ready for use.) It is cheaper to do this preparation at school and if teachers wish to do it, they should. Turn up the last two turns at each end, and direct a small blowpipe flame on them and touch them with hard solder that is coated with flux. Soft solder may give way.

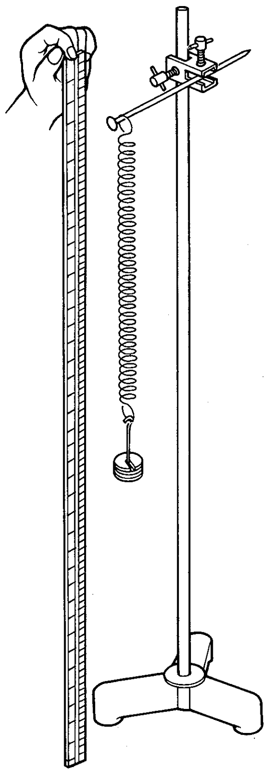
For children, it is better to have springs with coils separated; so the springs should be prestretched before they are issued – and at this stage it would be better not to do that publicly. To prepare the springs, experiment to find what load will stretch a spring a little beyond its original elastic limit in the coiled-up form, leaving the spring with its coils slightly separated. Then apply that load *gently* to spring after spring, so that one has a large supply of similar springs ready for use.

PROCEDURE

Offer spiral springs of steel piano wire, one to each child, even if they are working in pairs – it would indeed be frustrating to have one's partner spoil the spring without having a chance to do it oneself.

Find out all you can about these springs. Think of things to look for or to measure.

Children will need some scale for measuring stretches. Let them hold the scale beside the spring and make measurements somehow at first;



then go round to the children and offer a good stand with a firm clamp that will hold the scale in a vertical position beside the spring. Even then, children will have some difficulty in reading the stretches because they do not have a pointer. However, one can encourage them to use the bottom of the weight hanger or the end of the lower hook of the spring and mark its position somehow. This is an experiment that *could* be done with great precision, but young children would need detailed instructions and then the experiment would drag out into something that was no longer an interesting investigation of Nature. So we should accept rough measurements, but encourage care.

In their notebooks, children will want two columns, one for load and the other for stretch. They do not need a diagram of a spring being stretched – that is obvious to them and we shall not seem very sensible if we ask them to draw the obvious when they are busy doing an experiment.

It is worth while to encourage children to go on beyond the elastic limit. That does not mean we instruct them to do that. It certainly does not mean we mention the elastic limit, but it does mean we tell them they may 'spoil' the spring if they wish. We, as professional physicists, have a tendency to emphasize the straight-line (Hooke's law and elastic) region of behaviour; but to children all regions of the spring's behaviour should be natural, and if they investigate all regions they are perhaps being better scientists. (If the springs are made by spring manufacturers, they will be so cheap that we need not grudge the cost.)

This is a case for plotting a simple graph, if children are ready for it. Children take kindly to graphs provided they are introduced casually, not as something they 'should have done in maths', and unfortunately have not. To prevent the precision of plotting becoming a long burden, it is better to let children plot a rough graph step by step at this stage – and perhaps to encourage some who like neat work to take the graph home and plot it more carefully.

Looking for a rule

The teacher should encourage children to look for a simple story, some rule which tells how springs behave.

This seeking of a relationship is a scientific need that is not obvious to children of this age – it was strange to most of science until the time of Galileo – and we should not expect children to want to find a rule. (See however 'The remarkable role of the word "Constant"' in the *General Introduction*, p.46.)

We should praise those children who do see that stretch goes up in direct proportion to load but we should neither blame those who do not see that, nor give them a dictated conclusion. The aim of this experiment is to offer open-ended play with simple apparatus in a laboratory, to encourage children to work as young scientists for the moment: the aim here is not to enable them to extract a physical law at all costs and certainly not to give them a law to verify.

For many slower pupils the greatest benefit may come from just doing the experiment on one's own, in the form of a sense of possession. For many brighter pupils the greatest benefits may come from other things observed, other lines of inquiry pursued, such as yielding, twisting, bouncing, ... For all pupils we aim at a feeling of being an investigating scientist, and of enjoying that.

Like the lever law, Hooke's law is a clear story about behaviour in Nature; and the teacher should welcome it and tell children that Hooke himself was so pleased when he discovered it (just 300 years ago) that he kept it secret until he could arrange to make sure that he could get the credit for the discovery.

This is a clear, simple rule for springs that will be useful in making spring-balances, and even in finding out more about springs. If this kind of thing holds for other springs as well as yours, you have got some powerful knowledge.

Did this rule work for your spring of copper wire? Well, have another look. Yes, you can have more copper wire if you want.

Does this rule work for a rubber band (or a thread of latex rubber)?

Does it work for your steel-wire spring, on and on as you hang more and more on the spring for ever?

Answers to the last question will differ, because some children will have stopped at the place where 'our spring went wrong'; and that leads to a very valuable discussion which should be conducted quickly and gently without much emphasis at this stage.

All laws have limits – and that is one of the things a scientist has to know about. He does not just know the rules, or laws as he calls them, that tell him what happens. He has to know when things stop fitting with those rules. It isn't a case of rules going wrong – the rules are just a quick way to tell some of the story. And it isn't a case of Nature going wrong: Nature is what happens; Nature is 'true'. But the clever scientist knows how far the rules fit, just as the clever family doctor knows about healthy people just as much as about ill people.

Proportionality

In looking at measurements and graphs, the teacher should give admiration rather than a formal dictated conclusion. He should express a scientist's delight in a simple rule, a clear story about Nature. If children are not familiar with a straight-line graph he should help them to see that it shows proportionality: not by using a difficult mathematical description with some mysterious constant 'k' in it but by saying:

When you double the load, the stretch doubles; when you put on three times the load, you get three times the stretch; four times the load, four times the stretch: the stretch goes up in the same proportion as the load.

If you like, give children the words used by many a professional scientist when he is talking casually to colleagues: 'The stretch *goes as* the load.' (This is a sort of scientific slang; but it helps to carry pupils away from the mysterious formality of proportionality calculations. We can say, 'The cost of painting a wall goes as the area. The cost of material for a steel ball goes as the volume; but the cost of polishing its surface goes as the area – so that cost goes as the radius squared.') (See 'A feeling for proportionality' in the *General Introduction*, pp 44–46.)

If the laboratory has a board ruled in squares the teacher may give a first lesson on graph plotting with it. Prepared boards are available, which make this specially easy. The points are plotted and lines are drawn on a sheet of plastic, with a chinagraph pencil or a felt-tip pen. A grid of black lines is inserted behind the plastic to show the coordinate rulings. The marks on the plastic are easily erased. The teacher should plot a 'bogus' graph, not one that gives the show away by exhibiting the straight-line relationship – leave that for the delight of finding it for oneself.

If pupils bring the complaint that the spring twists round as it is loaded more and more, say:

Well, that is not my fault. That must be just what springs do. You have to take Nature as it happens.

Note on design A teacher with a taste for good design of apparatus may be tempted to offer a cure for that twisting trouble. He inserts a small swivel, like the swivel on a dog leash that prevents the dog from twisting the leash in his gyrations. One can buy tiny swivels from fishing supply shops. The swivel is inserted between the bottom of the spring and the load. Then the designer adds a good pointer below the swivel; and then he may suggest attaching a piece of mirror to the centimetre rule, to serve as an anti-parallax device for the pointer. By that time he will have made the experiment a better designed one, but far too complicated for these young people; and he will have spoiled their sense of doing it on their own. Such refinements of design belong in an A-level experiment and not at this stage – though at A-level we should not do that for a pupil but rather blame him for not devising some such things himself. The professional scientist finds himself forced by the difficulties which he meets to be ingenious and to develop his own aids. He does not have a teacher to do it for him. So here we must restrain our enthusiasm and let the children experiment in their own simple way.

Stretching a wire

Pupils should learn that a plain metal wire stretches when pulled, following the simple Hooke's law story, up to a limit which is often near to the limit for yielding. They will have found a closely similar behaviour with their springs. It would be best if we could give them copper wire to load up and measure for themselves; but the stretches in the Hooke's law region are so small – the maximum stretch before yielding is of the order of one millimetre per metre of wire – that pupils cannot make convincing measurements in their own experiments without having special devices which are not suitable at this stage. They can feel the wire's stretching qualitatively themselves but even that needs some care; and they are likely to go beyond it into the yielding region before they know what they are doing, unless they have a general idea what to look for.

33 Demonstration
Stretching a wire

APPARATUS *item no.*

1 Reel 26 SWG bare copper wire (new) *2C*
1 Hoffman clip *10V*
2 Single pulleys on clamps *40*
2 Weight hangers with slotted weights (100 g) *31/2*
1 Weight hanger with slotted weights (10 g) *31/1*
1 G-clamp *44/1*
1 Needle (darning needle or thin knitting needle)
1 Drinking straw *4A*
Evostik
Thread

PROCEDURE

We suggest that the teacher should give a demonstration of the stretching of a copper wire first and then ask pupils to do a class experiment to feel the stretching qualitatively. This is a reversal of our usual policy of urging teachers to let the children do their own exploring first and then, if necessary, sum things up with a demonstration. In this case, we think the reversal of order gives pupils needed preparation; but there is no reason why teachers should not, if they prefer, give the class experiment first.

For the demonstration, we can have a longer test wire if it is horizontal. The wire should be carefully anchored to a table at one end of the classroom and loaded by using weights and a pulley at the other end. We make its very small stretches roll a sewing needle which carries a straw as a pointer. We cannot do that by wrapping the wire itself round the needle, so we use an auxiliary thread wrapped round the needle, which is held in a simple bearing. One end of the thread is attached to the test wire near the loaded end. The other end of the thread carries a small load hung over a pulley to keep it taut. As the test wire stretches, the thread moves as well and rotates the needle and pointer.

As loads are added to stretch the test wire, the pointer makes quite large movements, proportional to the additions of load. When the wire yields, the pointer makes huge movements and if a small piece of cotton wool or other marker is attached to the wire, pupils can see the motion of the wire itself. The test wire must be gripped very carefully at each end; otherwise it will break in places where it is damaged.

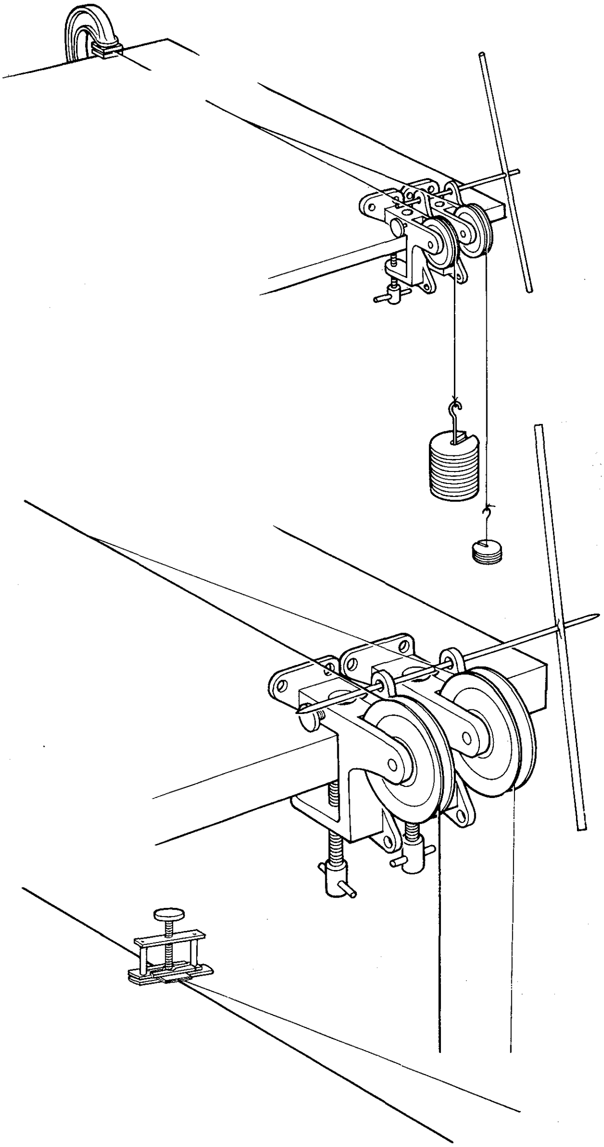
We hope that this demonstration will be so simple that children understand the arrangement clearly. Using more complicated arrangements, such as a vernier and scale, drags the story into details that obscure the delightful discovery of Hooke's law stretches and then the surprising yielding of the wire.

For this demonstration we should use fresh copper wire and give it some careful treatment before the demonstration, to straighten out kinks and give it a 'memory' of cyclical loading and unloading. We should continue beyond the elastic limit and show the wire making a large yield, and then breaking to make a sharp point. Children should feel the broken end point and look at it with a magnifying glass.

Clamp the end of a suitable length (not less than 1.5 m and preferably at least 2 m) of the copper wire between two small polythene pads and secure rigidly to the end of the bench with a G-clamp.

At the other end of the bench, clamp the two pulleys as close together as possible. Pass the end of the copper wire over one of the pulleys to the larger weight hanger which should be about 45 cm above the floor.

About 60 cm from this pulley, stick the end of a length of thread to the wire with Evostik. After the glue has set, pass the thread over the second pulley and hang the light hanger from it so that the base of this hanger is about 30 cm above the floor. (Alternatively, use a Hoffman clip with two small pieces of sheet polythene as jaws to hold the thread and wire together.) Put four 10-g weights



on this weight hanger to make a total of about 50 g. This load, which is not changed, serves to keep the thread taut.

Pass a needle through the two holes in the pulley clamps – as illustrated. Take a single turn of the thread round the needle, and push the needle point through a drinking straw to form a pointer. When all is taut, the position of the tip of the drinking straw is noted.

The 100-g weights are then added to the load on the wire. As the wire stretches, the thread will move and rotate the needle. This movement will be shown by the movement of the tip of the pointer. An additional 500 g added to the wire can be expected to shift the position of the tip of the pointer about 3 cm per metre-length of the wire.

If now the load is taken off in 100-g steps the pointer will return to its original position thus revealing the elastic nature of the stretching.

If now the wire is reloaded in 100-g steps to a total of about 1500 g (using a second weight hanger as well as the first), the wire will yield visibly. (At an extension of about 30 cm, the weight on the thread will reach the ground and disengage so that the assembly is protected from damage as the wire yields gently through a considerable distance.) The loading should be continued until the wire breaks. This can be seen very clearly if a flag of, say, cotton wool is stuck to the wire about 30 cm from the metal channel.

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34 Class Experiment

Stretching wire

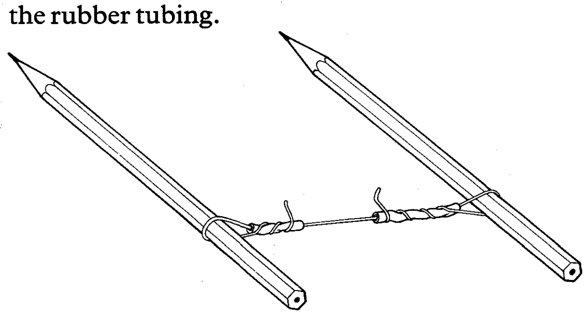
APPARATUS *item no.*

4	50-g reels of 32 SWG bare copper wire	*2B*
2	10-cm lengths valve rubber tubing	*2F*
32	Pencils or wood dowels	
32	G-clamps	*44/1 and 44/2*

PROCEDURE

Each pupil should have a good length of the 32 SWG bare copper wire (say, 1 m) with which to see and feel the stretching of the wire when it yields.

Each end of the copper wire must be secured to a pencil or wood dowel. It is not satisfactory merely to wind the wire round several times and twist the end as it weakens the wire and it is likely to break at the twist. The simplest arrangement which obviates this difficulty is to put about 2 cm of valve rubber tubing on the wire near each end, to put two turns of wire beyond the tubing round the pencil and then four turns of the end around the rubber tubing.



Ask pupils to pull the wire gently, trying to feel the elastic stretching of it. Then they should pull more strongly and feel the 'cheesy' yielding. That is a surprising experience to young children, and a very surprising experience to many a mature physicist. Therefore in this experiment we must give each pupil a wire for himself. It would be silly to let pupils work in pairs with one pupil relying on what his partner feels.

Each pupil should continue stretching his wire until it breaks. Teachers who are familiar with the dangers of a steel wire whipping when it breaks need not worry about dangers with copper wire. These thin wires with their cheesy yielding are not dangerous.

Each pupil should examine the end of the wire where it breaks with a magnifying glass or under a microscope and perhaps feel whether it is sharp by pushing it against his arm or cheek.

NOTES

1. It is essential to take fresh wire off the reel each time the experiment is done and all bending or kinking must be avoided. Each pupil should pull out a length of wire and lay it full length on his bench while fixing the ends.

2. With very fine wire, some pupils will dispense with the dowel in their hand and wind the wire round their fingers.

Feeling forces

At the end of this year, we shall introduce simple ideas of energy changes in which drawing upon use of fuel enables us to do useful jobs. And we shall return to energy and expand our treatment in each succeeding year.

This year, the useful jobs involve pulling or pushing with a force, to raise a load or stretch a spring. Therefore we need to introduce the idea of forces, simply as pulls and pushes, some time during this year. (We shall still regard a force as a pull or a push in later years and shall measure forces by counting the number of standard pulls in parallel, assuming forces to be additive.)

For this year, a very simple feeling for force – which many children may already have – will suffice; and we hope teachers will postpone any careful discussion of forces and their measurement to a more mature stage in a later year. However, we do need to bring pupils' feeling for force to the surface and to attach the name 'force' to it. So we should give them the following short play with forces. This is suggested as fifteen minutes of play, with only a simple comment. It would be unwise to expand the discussion.

35 Class Experiment
Feeling forces

APPARATUS *item no.*

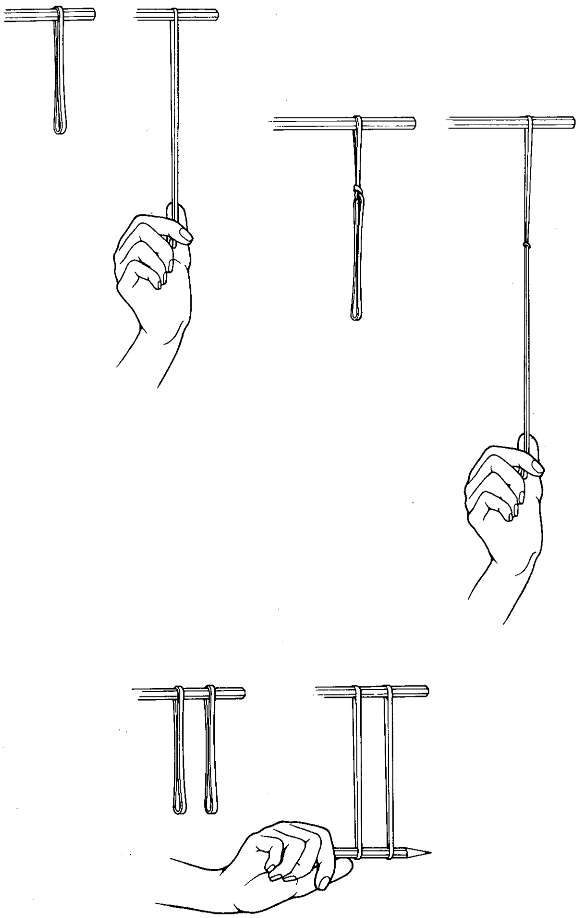
64 Rubber bands
32 Steel springs *2A*
32 Lengths of string
32 Pairs of cylindrical magnets *50/1*
8 Wide steel springs *2D*
8 Latex foam blocks *2E*
16 Lengths of elastic cord *2G*
16 Soft erasers for twisting *2H*

PROCEDURE

We could say:

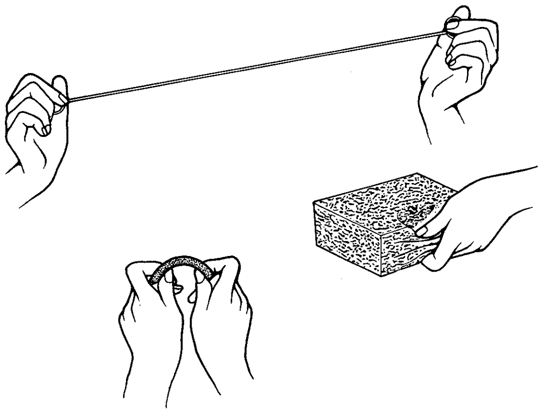
You have been applying forces to your spring. Feel some forces for yourself. Springs and rubber bands pull when stretched. Feel the force. Then hold several rubber bands side by side and pull. Feel a string pulling in the same kind of way, though you can hardly see the stretch. Hold a lump of metal in your hand or hold it by a string. You can feel it pressing down. It behaves as if something is pulling it down.

There is a pull on it (from the Earth, perhaps) that you can feel. We call that downward force the 'weight' of the lump.



Next try feeling forces with two magnets. Give two bar magnets to each child; but no iron filings at this stage since we are only looking for forces, and particularly repulsions. We do not even give any names such as poles. We give the words 'repel' and 'repulsion' as grander names for 'push'.

Try stretching, squeezing, twisting some of the other things – the wide steel springs, the rubber foam blocks, the soft rubbers. All these should go quickly, because there are no clear conclusions or detailed records to be made; it is a matter of seeing, and increasing one's acquaintance with Nature.



Some pupils may continue on their own with rubber bands at home.

Atoms and elasticity

The teacher should comment on both the strength and stretching of wires and springs, from the point of view of atoms. The atoms are regularly arranged, close together, in crystals of a metal wire. Left alone, the atoms attract their neighbours and at the same time elbow their neighbours away (repel them) with forces which just cancel out. Each atom is, *on the average,* in equilibrium, but if we compress a rod, pushing the atoms closer together, we increase the elbowing set of forces (the repulsions) more than we increase the attractions. And if we try to stretch a rod or wire those repulsions decrease more and we feel the attraction holding the wire together.

A short word about sheets of atoms slipping over one another could go in here. Unless models of crystal structure are available in a form that allows this to be illustrated, we can only say a little about it. (We should not picture the crystal structure as being torn apart in this process of a metal yielding. That would be nearer to melting or even evaporation.)

It is possible nowadays to make large single crystals of metal by special heat-treatment, and those show interesting deformations when sheets of atoms in the crystal slide over one another as the material is stretched beyond the elastic limit. With ordinary samples of metals, such as we meet in wires, the structure is much more complicated. A common copper wire is not a single crystal but a collection of many small crystals with boundaries at which large forces may come into play to resist distortion. And within the component crystals there are likely to be 'dislocations' – where, for example, a line or sheet of atoms is missing or displaced a little – at which the yielding is likely to start. Teachers who wish to have a more detailed account of the behaviour of metals should consult N. F. Mott, *Atomic Structure and the Strength of Metals* (Pergamon).

If the crystal model made of large polystyrene balls has been made with balls stuck together to make layers that can be moved separately, teachers should show that again now, sliding layer over layer to illustrate these changes.

Note on atomic and molecular forces We should go into no more detail than that with children. The real story, which we would like to think so simple, is really quite complicated. The attractions between atoms are fairly short-range forces, as we know from the fact that two pieces of metal placed side by side do not attract each other.

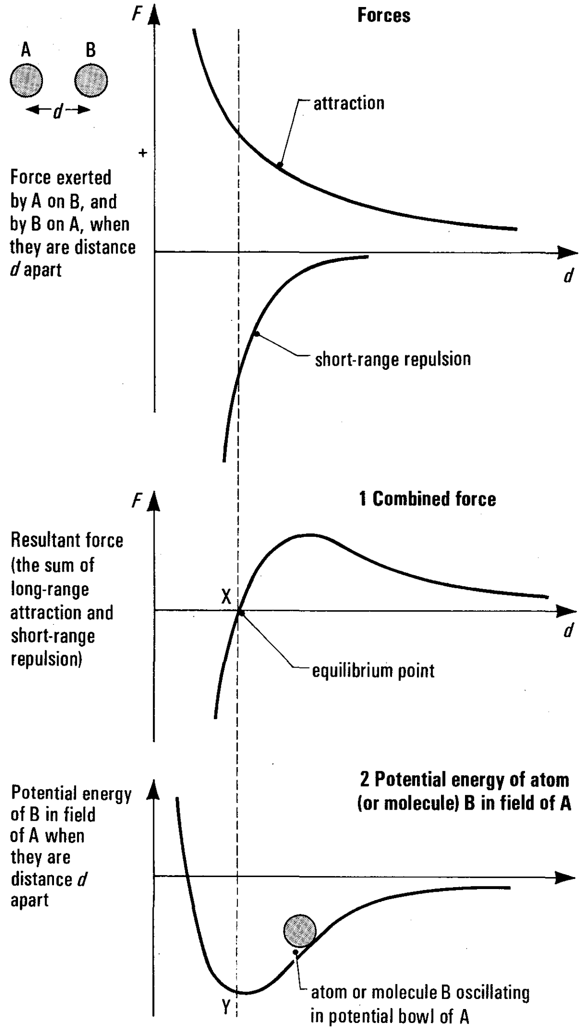
Even the *short-range* attractions extend only a few molecule diameters out from a molecule at most. We know that from investigations of surface tension. For example: the tension of a flat soap film remains constant as we stretch it thinner and thinner. (It only changes a little, by the migration of different concentrations of soap, to provide for the extra strength needed, in the upper regions of a vertical film, to carry the weight of the film below.) If strength is independent of thickness, right down to very thin films, that suggests that only the two thin outer layers, each thinner than half the thinnest film, provide the tension while the middle section of the film contributes nothing. We argue this because we see that it does not matter how thin that middle section is.

The *very short-range* repulsions only appear noticeably at still closer approach, a small fraction of a diameter. Reflect that that is just what we think when we picture gas molecules colliding with each other. (For a macroscopic model, think of two billiard balls repelling as they collide.)

We may imagine some slight attractions such as those shown by the a/V^2 term in Van der Waals's expression – a term which grows to a very large value when the gas condenses to a liquid. We think of the repulsive forces as not appearing at all until one molecule goes smack against another in the collision. Of course, really, there is no 'smack': that is only the very sudden slowing, stopping and starting away again of the molecule in the strong field of force of the repulsion. These attractions and repulsions can both be 'explained' on the basis of quantum mechanics.

The repulsions between atoms must also be there, or solids would collapse under their attractions, and these repulsions must also be short-range forces; but they cannot have the same falling-off with distance as the attractive forces – otherwise the atoms in solids would never settle down to a definite spacing as they do. In fact, the repulsions are very short-range forces, not appearing significantly until the atoms are so much closer than when they first feel attractions. And then the repulsion rises sharply as atoms move closer, until it balances the attraction. It is this difference, between attractions which grow with decreasing distance and repulsions which grow much more steeply with decreasing distance at close approach, that provides the elastic properties we see.

If we investigate the force exerted on an atom by a neighbour at various distances, the graph of force against distance looks something like the sketch (1). Or the graph of potential energy of the two atoms looks something like graph (2). If we have only these two atoms in a system, the equilibrium position to which they should settle down will be shown by the point X on graph (1), where the resultant force due to one atom on the other is zero, or on graph (2) at the point Y (with the same separation) where the potential energy is a minimum. In practice, they do not 'settle down' but remain in vibration about that equilibrium position, so that if we think of one atom as fixed the other one is, so to speak, sliding up and down the sides of the potential-energy bowl around Y. For an atom in the middle of a solid, we must take account of many neighbours on every side and the picture is more complicated.



Both the repulsive forces and the attractive ones between atoms are electrical in origin, arising from the charged particles composing one atom disturbing those of a neighbour, in ways that are specified by quantum mechanical rules. Since these forces are due to complexes of charges, they fall off more rapidly with distance – much as the field of a bar magnet does – than the inverse square law force between isolated charges or gravitating masses.

Nuclear forces act over a far shorter range still, becoming inappreciable at distances thousands of times smaller than the range of repulsions between atoms in collision.

This is all too difficult for children to think out or enjoy knowing about at this stage, but it is something that we as teachers should think out in our own minds.

CHAPTER 6

Air pressure and molecules

Squashing air; what air pressure can do; inventing a model for a gas

Now our work takes an imaginative turn. We return to gases, measure pressures, describe a very simple kinetic theory, and speculate about the mechanism of gas pressure. Just telling a romantic story about gas molecules in motion would be jumping too far ahead into unsupported 'knowledge', but for the Brownian motion, which gives strong suggestive support. So we make sure that every pupil sees the random motion of smoke-specks for himself. We practised with microscopes early in the year to prepare for this, to give the Brownian motion a fair chance to be seen and understood.

Force and pressure; some questions to start with

Before developing the main theme of the chapter it is wise to offer some introductory work relating the children's simple, informal ideas of force and of pressure. So the chapter in the *Pupils' Text* starts with some questions about some experiences which bring these ideas out. These 'thought experiments' link pressure with both a force and with an area – the area over which the force is spread.

Such thought experiments can readily be supplemented at the bench. Try pressing on the bench top with the palm of the hand and then, using an equal force, on the corner. Hold a ruler in the hand and squeeze it by its edges and then by its flat surfaces. Or lean with arm outstretched and a flat palm against a wall – and then against a corner of a wall.

Atoms and molecules in solids, liquids, gases

We think of solids as made up of atoms arranged in a regular array, close enough together to exert strong forces on each other when moved – repulsions if we move them nearer together, attractions if we pull them farther apart. The forces of neighbours combine to hold the atoms in the regular patterns which make solids form crystals.

In liquids the component particles – molecules – are free and moving fast enough to be able to move short distances before meeting strong forces from a neighbour: collisions are very frequent, spaces between molecules are very small, but yet there is general freedom to migrate, and the concerted forces that tie them in crystals are only felt in small local patches.

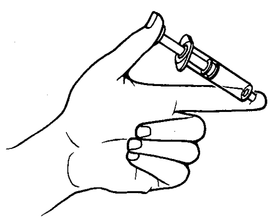
The higher the temperature, the more the motion: the bigger the amplitude of rapid vibration in solids and the higher the speed of the irregular motion of molecules in liquids.

We should have such pictures in our mind in teaching children now, and in later years we should give some such descriptions and encourage children to use them in thinking about the behaviour of solids and liquids. But at this stage, the story is too complicated and unsupported. Gases, however, offer us properties which let us speculate in a simple way about their 'molecular' behaviour; so we can start on a very simple discussion of gases this year.

36 Class Experiment
Squashing air

APPARATUS *item no.*

16 Nylon syringes *6D*
Several bicycle pumps



PROCEDURE

Gases are squashy: let the children compress air and feel its springiness, using a nylon syringe with a finger over the needle end. Or use a bicycle pump – which the laboratory should have, unless many of the pupils have them. Ask pupils how they could tell whether it is the air that makes it difficult to press the piston down, the air that they can feel pressing back, or the piston rubbing against the barrel. Progress will not be held up if the children do not answer this. It is wise not to give an answer but to leave this as a puzzle for children to think about as young scientists. (We have to give an answer only too often, and that is liable to build up a picture of science as a set of answers and even a picture of scientists as answer-givers. We should seize every opportunity we can of leaving a question with children; and only when we notice someone really unhappy should we quietly give him or her the answer that he needs for his sense of security.)

Ask what makes air press on things, or how air presses on things, and leave that question unanswered until after further study of air pressure. Remind children that gases do press on things strongly, and do move easily.

Shut your mouth and puff out your cheeks and feel your cheek with your finger. Feel the lightly compressed air in your chest driving out through your mouth and nose when you breathe out. Hear carbon dioxide bursting out from a bottle of soda water. Feel gas escaping from a cylinder, and listen to it.

Gases can make a considerable pressure on anything that holds them. *How* do they make that pressure? What *is* pressure?

Teaching about pressure We should like to introduce the idea of fluid pressure and lead to the use of pressure gauges by a series of simple steps of demonstration and class experiments. With pupils of this age, we must certainly teach pressure by some empirical approach if we teach it at all, because a theoretical approach based on laws of fluid equilibrium would carry no conviction.

We might take a crude empirical view and offer various pressure gauges for use, hoping that pupils will see that they agree with each other in what they measure. This will not tell pupils what that common measure is, namely, *force per unit area*. That is because we do not have, among the ordinary pressure gauges, a direct 'force-per-unit-area-measurer'.

We wish we could choose one common form of gauge, such as water in a U-tube, and attach it to a reservoir of water in which a piston of known cross-section with a known force driving it applies a pressure which could be calculated by dividing force by area. Unfortunately, the latter simple apparatus is difficult to construct in any form that works consistently, without encountering difficulties of friction or expense. The Nuffield Physics group has experimented with a polythene bag (or a balloon) with water or air in it, subjected to pressure by a square block placed on it and carrying a load. But in practice, tensions in the envelope apply extra forces and make the observed pressure quite different from the simple one expected. Teachers who have tried such apparatus find that with practice, and some careful explanation to pupils, they can obtain results which give general qualitative support to the idea that the manometer is measuring some quantity like force/area; but we do not consider most of the forms we have tried behave sufficiently well to be suitable for general use.‡

Much ingenuity has been brought to bear on this problem, in the hope that we could devise apparatus that would show pressure being produced clearly in the form of a force applied to an area and being carried across to secondary pressure gauges, such as U-tubes and Bourdon gauges, in a way that would make the concept of pressure

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‡ This approach seems to be very good, but it leads to trouble. Since it has proved a very tempting field for ingenious schemes, we would like to offer teachers a short account of the essential difficulty.

The general basis of such schemes is to connect a polythene bag filled with water to the manometer which is to be used for comparison. We place a small flat platform, 10 cm by 10 cm, on top of the bag, and place loads on that platform. We hope to find the manometer reading proportional to the load. And when we change to a platform of different area, 20 cm by 20 cm, we hope to see that it is load/area which determines the manometer reading.

However, loading of the platform pulls the surrounding sheet of polythene into such a shape that its tension exerts extra forces on the platform. That happens whether we have filled the polythene bag fully or have filled it only partially, leaving a lot of loose fabric. Those forces modify the story.

Suppose, for example, the bag is confined in a vertical cylinder; and the pressure is imposed by placing a load on a small platform on the open top surface of the bag. The pressure generated in the water inside the bag will be independent of the area of the platform. To see that, consider the force on the closed bottom of the cylinder. There at the bottom, the thin polythene envelope is pushed into contact with the bottom of the cylinder. The pressure of the adjacent water is transmitted straight through it to the bottom of the cylinder and produces the force which would be felt by anyone holding the cylinder. That force is the area of the bottom of the cylinder multiplied by water pressure just above it. Since the polythene envelope is necessarily flat in that region, its tension does not modify the force. But the force on the bottom of the cylinder is simply the weight of water plus the weight of platform and load. Therefore the pressure inside is simply that which would be produced by the load applied to the complete cross-section area of the cylinder. The area of the little platform disappears from the story.

clear to pupils. We do not have a simple method that is wholly successful. Again and again we are led back to the difficulty described in the footnote. The best we have been able to devise is the Evesham pressure-teaching apparatus described below. We suggest it should be used for a rough demonstration accompanied by a short description of pressure; and the pupils should then proceed to measure pressure with water manometers, barometers, and Bourdon gauges – postponing a more inquiring discussion of pressure to future years.

Thus our treatment offers acquaintance with some new instruments and some new phenomena, such as atmospheric pressure, without at this stage building a systematic knowledge of the quantity being measured. In treating pressure like that we are not fully living up to our principle of teaching for understanding. Unfortunately this is a region where a difficult concept and unruly apparatus combine to make the essence of the topic too hard for pupils of this age. Yet we need familiarity with pressure gauges so that we can carry pupils on to barometers and the idea of atmospheric pressure and its measurement; so that we can link that in turn with a simple molecular theory of gases.

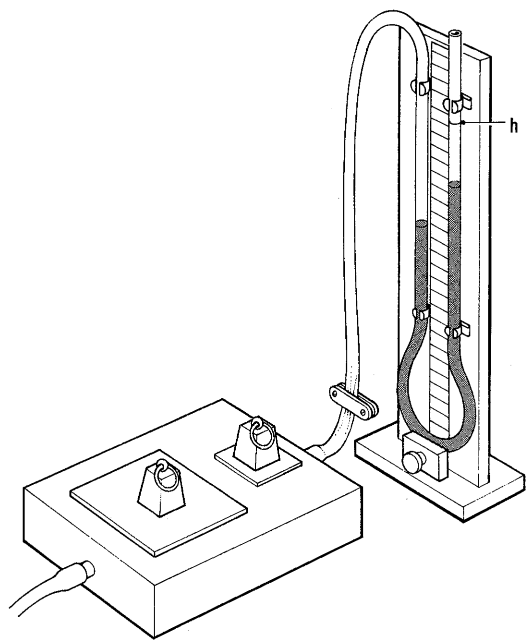
37 Demonstration
Discussion of air pressure

APPARATUS *item no.*
1 Evesham pressure box *41*
1 1.2-m mounted U-tube *6G*
2 Slotted bases *30*
5 $\frac{1}{2}$-kg weights *36*

PROCEDURE

The pressure box is made of hardboard about 40 cm long, 20 cm wide and 5 cm deep. It is lined with plastic sheet and fitted with two brass tubes, one at either end. Two square holes are cut in the top, one 10 cm square and the other 20 cm square. Square, loose lids of hardboard are provided to fit these holes. One of the tubes is connected to the water manometer. The other is connected to about a metre of tubing into which the teacher can blow. The plastic lining then fills with air and pushes up the free hardboard lids until one or both lifts above the top of the box.

At this stage, the lids are loaded with weights placed carefully at the centre of each. Start with $\frac{1}{2}$ kg on each lid and blow in more air gently. When



the pressure has increased sufficiently the large lid lifts, but the small lid stays down.

Then load the large lid with two $\frac{1}{2}$-kg weights placed symmetrically, keeping one $\frac{1}{2}$-kg weight on the small lid. Increase the pressure and the large lid still lifts. Then load the large lid with three $\frac{1}{2}$-kg weights. Increase the pressure further and the large lid lifts. Then load the lid with four $\frac{1}{2}$-kg weights, still keeping one $\frac{1}{2}$-kg weight on the small lid, increase the pressure until it can lift a lid. At this point we expect both lids to rise, and both do.

Then load the large lid with five $\frac{1}{2}$-kg weights, and increase the pressure still more. At this stage we hope to see the small lid rise and not the large one; but we may well find that both lids rise. This is the weakness of the experiment and it would be wise to warn the pupils of some such weakness beforehand. (The failure to give ideal behaviour is perhaps excusable since the last increase in load on the large lid is only 20 per cent, whilst the first one was a doubling of the load.) With still bigger loads on the large lid we may expect to see the small lid lift alone.

This is not a perfect demonstration but we believe it will help greatly in connecting the idea of pressure as force/area with the behaviour of the working gauge that we will use for other experiments.

After this demonstration and a short description of pressure, pupils should proceed to measure pressures with water manometers, barometers, and Bourdon gauges, postponing a more inquiring discussion of pressure to future years.

Thus, our treatment offers acquaintance with some new instruments and some new phenomena, such as atmospheric pressure, without at this stage building a systematic knowledge of the quantity being measured.

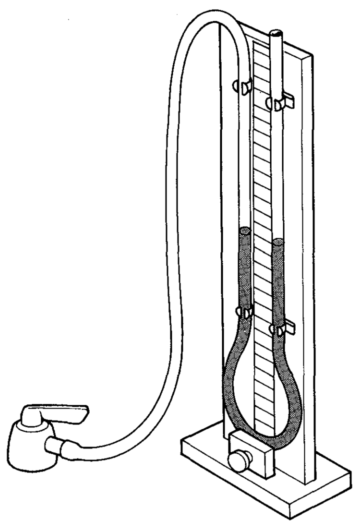
Comparing pressures

The pressure of the air inside the box was also supporting the load of the length of the column of water in the U-tube. That suggests that the U-tube provides us with a convenient way of comparing gas pressures.

38 Class Experiment
Comparing pressures

APPARATUS *item no.*

8 U-tube manometers *6A*
8 Slotted bases *30*
1 Bottle of methyl orange *6C*
8 Lengths of Bunsen tubing
16 Metre rules *501*



PROCEDURE

The manometers should be half-filled with water (coloured with methyl orange) and connected to the gas supply by Bunsen tubing. The gas taps are turned on (and kept on) and the difference in levels in the manometers is measured.

39 Class Experiment
Measuring lung pressure

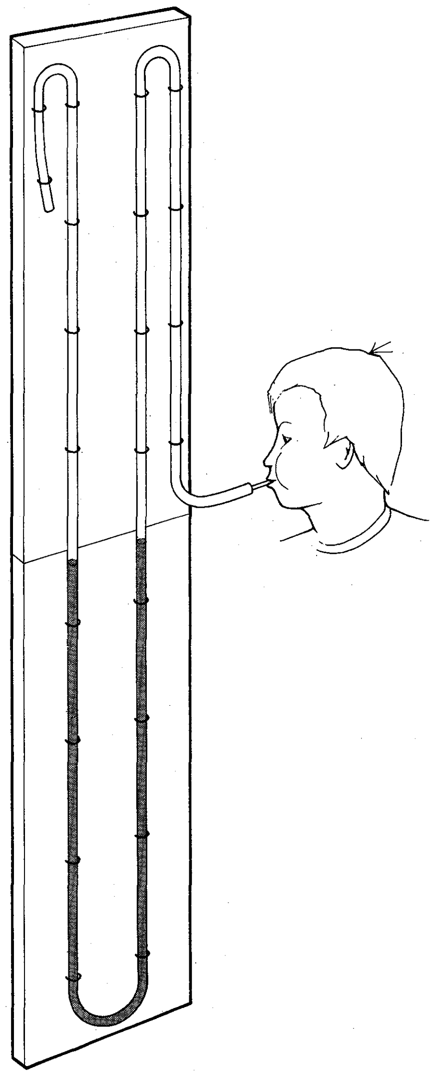
APPARATUS *item no.*

2 2.4-m mounted U-tubes *6F*
1 Sterilizing bath
32 Mouthpiece tubes *6M*
1 Bottle of methyl orange *6C*

The large U-tube manometer is made of transparent plastic, secured to a board. Preferably it should be attached to the wall.

For hygiene, 32 mouthpieces are necessary – i.e. 5-cm fire-polished glass tubes to fit the tube. Each pupil can fit his own tube to the manometer.

The sterilizing bath for the glass tubes can be a large beaker or, better, a wide cystallizing dish, of dilute T.C.P. or alcohol.



PROCEDURE

Move over to an enormous U-tube on the wall of the laboratory. This should be made of transparent plastic for safety. It should run from ceiling to floor to ceiling and then down to shoulder level for pupils to blow into it and it should be filled half-way up with water coloured with some harmless dye. (The dye should be dilute for the sake of the floor when accidents occur.) Let pupils measure their lung pressure by blowing on this manometer, making notes of the measurement in centimetres of water. Setting up these tall manometers takes considerable time and trouble. If there is a convenient place on the wall of the laboratory where they could be set up and kept available for use, that would be good.

Pupils will be delighted to find that they can bounce the water in the manometer, and with suitable attention to resonance can bounce the water up and out. This is a delightful but messy activity which one discourages by definite discipline with older students, but with these young people the teacher should welcome it if possible, because to them it is simply part of putting the apparatus to every use and it even leads to ideas of resonance. A clever teacher will actually point to the mechanism of resonance (without naming it) and store it up for future use.

Children who wish to should try to see how far below atmospheric pressure they can go on the manometer, by 'sucking'. Just let them do this, but do not at this point get involved in a discussion of pressure excess or defect compared with atmospheric, because that follows more easily after barometers.

NOTE

It is easier to avoid air bubbles in the manometer if the tube is filled before fixing it to the board. Make a preliminary estimate of length of water column required, immerse one end of the tubing in a beaker of coloured water, suck at the other end until there is the required length and finally fix the tube to the board.

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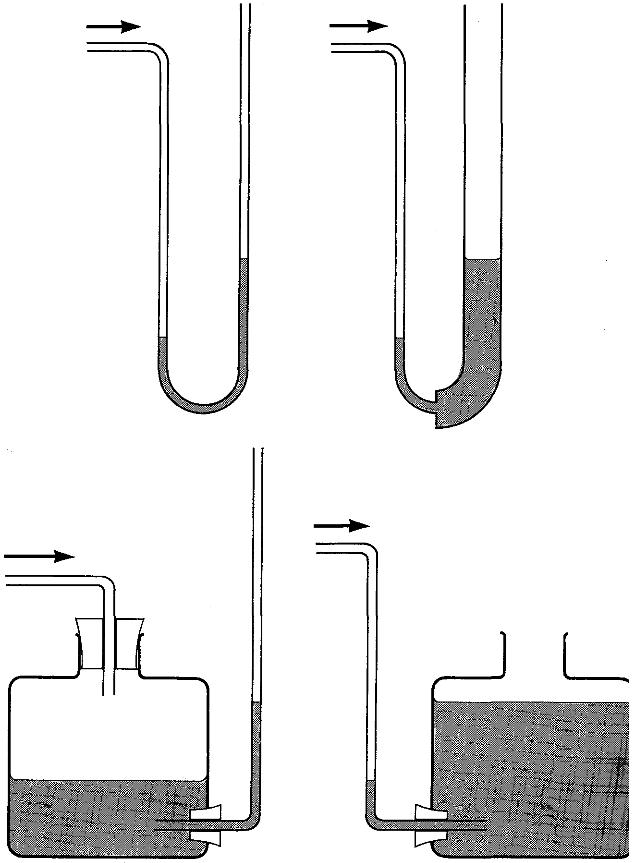
40 Demonstration
Using manometers with unequal arms

APPARATUS *item no.*

1 1.2-m mounted U-tube *6G*
1 60-cm manometer with unequal limbs *6H*
1 Aspirator (10 litres) *523*

PROCEDURE

'Would it make any difference to the manometer reading for a given pressure if the cross-section area of liquid were changed on one side?' As a demonstration, show the effect of the local gas supply on a small water manometer, with equal cross-section in both arms, and on another in which the arms are somewhat unequal, and finally



on one with very unequal arms. The last one is made by using an aspirator jar with an ordinary glass tube coming out from the spout at the bottom, and bent up to represent the 'narrow' arm of the U-tube, while the main jar represents the wide arm. Apply the gas supply to the narrow arm and then to the wide arm (by a tube through a cork in the neck at the top).

Children will find to their surprise that the level of difference is the same both ways. Leave these U-tubes with different arm-proportions for a week as a demonstration. If children say, 'That shows that water finds its own level', we should respect this old proverb as part of our heritage of simple science at this stage.

Note The traditional discussion of pressure and rules for fluid-pressure behaviour is a delightful example of carefully built-up physics that can be taught well; but that will take more time than we should spare in this course, and it would concentrate attention on formal material that children would memorize; so we wish to experiment on doing without that material in this course. At the moment 'Water finds its own level' will be a primitive substitute for some of that knowledge; and the rest of it will be acquired, in passing, in later years.

41 Demonstration
Using manometers with different liquids

APPARATUS *item no.*

2 U-tube manometers *6A*
2 Slotted bases *30*
1 Bottle of methyl orange *6C*
1 Length Bunsen tubing
2 Metre rules *501*

PROCEDURE

The manometers should be half-filled, one with water and one with mercury, and connected to the gas supply with the tubing. The water may be coloured with methyl orange. The gas taps are turned on (and kept on) and the different levels in the manometers compared.

This will raise the question of comparing mercury with water for pressure measurements; and we should simply point out that this is a matter of relative density.

42 Demonstration
Comparing two liquids

APPARATUS *item no.*

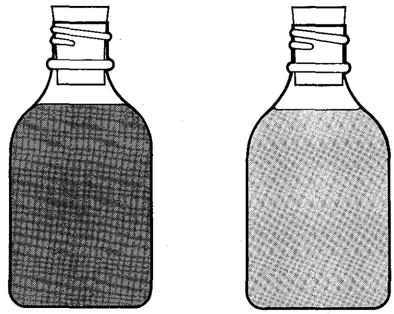
2 Small medicine-type bottles *534*
1 Balance *42*

The medicine bottles must both be equal in size and shape. One is filled with water, the other with mercury. Both are securely corked.

PROCEDURE

Weigh a small bottle of mercury and an equal bottle of water and ask how the comparison should go. This is something better done by the teacher, or children will spend too much time on arithmetic rather than profitable puzzling.

When that comparison yields the proportions



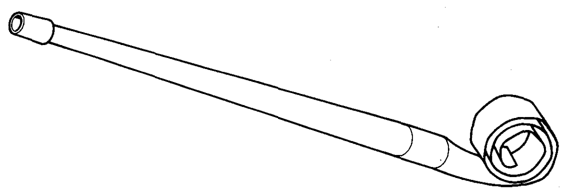
$13\frac{1}{2}:1$ for mercury to water, suggest that the pressure gauge will show the same ratio the other way round. Take the mercury level difference for the gas supply and multiply it by $13\frac{1}{2}$.

43 Class Experiment
Another pressure gauge – the Bourdon gauge

APPARATUS *item no.*

1 Bourdon gauge *67*
32 Paper Bourdon gauges *6B*
1 Foot pump *45*

The Bourdon gauge reads pressure from $0–1.5 \times 10^5\ \mathrm{N\,m^{-2}}$ and should, at sea-level, normally read $1 \times 10^5\ \mathrm{N\,m^{-2}}$.



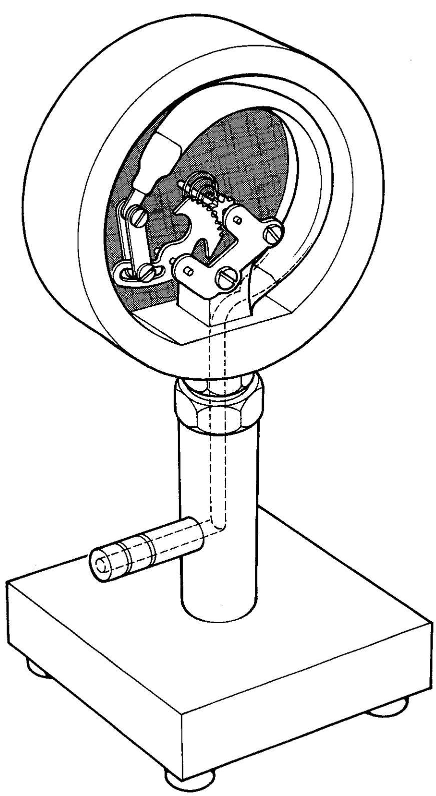
PROCEDURE

Introduce a Bourdon pressure gauge by using it to measure excess lung pressure. If the effect of a pupil blowing is not sufficiently impressive, try connecting a foot pump to a Bourdon gauge and pumping gently.

Show a paper toy 'Bourdon' and explain very briefly that it works by the pressure inside making the flattened tube uncoil.

NOTE

The Bourdon gauge is essentially a pressure-difference gauge. In this teaching it is best to arrange for the gauge to read normal atmospheric pressure (very nearly $10^5\ \mathrm{N\,m^{-2}}$) when open to the air. Teachers working in schools at high altitudes will need to adjust the gauge appropriately. (See illustration overleaf.)



ATMOSPHERIC PRESSURE

With many children at this age the idea of the atmosphere is half taken for granted, half unknown. Asked if the air is here in the room, a child will say, 'Of course it is, I breathe it in and out, I can feel it.' Yet when asked if air is real stuff that you can weigh and put in a box, like water or sand, most children will show uncertainty. Air is not as real to them as water or sand – nor was it to the scientists among our early ancestors. And the idea that we live at the bottom of an ocean of air that exerts as good a pressure as an ocean of water some 10 m deep is new and strange – essentially unthought of rather than difficult. (James Conant, in his excellent discussion of the tactics and strategy of science, quotes this idea of 'ocean of air' as an example of a conceptual scheme that enables science to advance.) Children in this course have met one aspect of the reality of air when they saw air being taken out by a vacuum pump. But now we must push the question further and ask them how they know the air is really there and what they think it does.

Children will tell us, by hearsay, that the air exerts a pressure, pushes on things. We ask, 'Well, if the air does press on everything, could we use the U-tube and mercury to measure the pressure of the air in this room, the pressure of the atmosphere as we call it?' (If someone asks, 'Why mercury?', reply, 'Let us try it with mercury first, in case the pressure is so big that the water pressure gauge is not tall enough.' This is not quite the same as the discouraging reply, 'Because the mercury one is the right one to use': it is nearer to the sensible admonition 'Try the 10-amp ammeter before you try the 1-amp one!' That is good scientific procedure, and we should say so now, or some years from now.)

If pupils do not know what to suggest, point out that each of the U-tube pressure gauges so far has had two pressures, one on each side, the lung pressure on one side and the atmosphere on the other side – assuming for the moment that the atmosphere *is* with us and *does* press on things.

44 Demonstration
Atmospheric pressure shown by pumping out air on one side of a mercury-filled U-tube manometer

WARNING When these experiments are demonstrated, ensure that the laboratory is well ventilated.

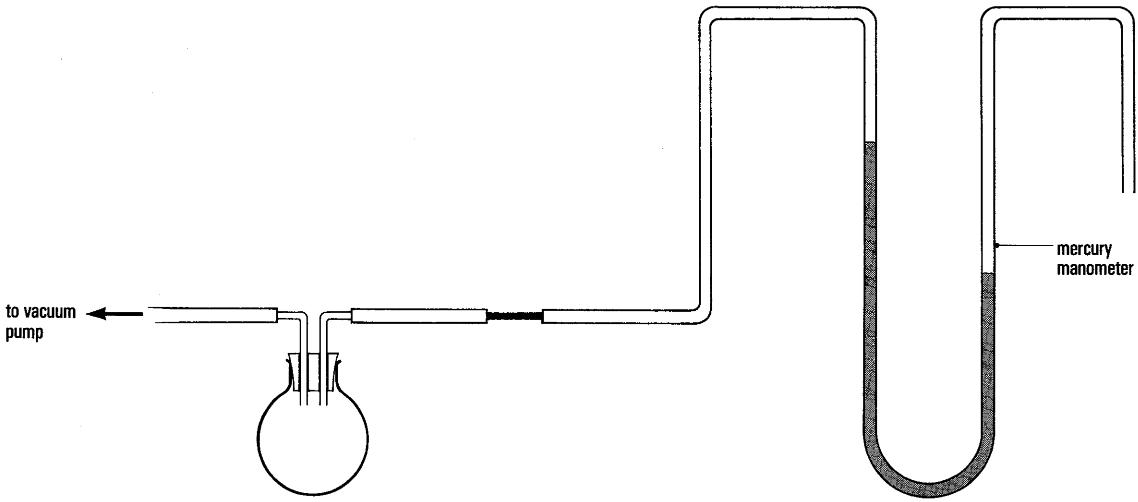
APPARATUS *item no.*

1 1.2-m mounted U-tube *6G*
1 Bottle of mercury *535*
1 Length of pressure tubing *10DD*
1 Vacuum pump *13*
1 Mercury tray *524*

PROCEDURE

Now look at the U-tube. Both ends open, not connected to anything. There is the mercury at the same level on both sides. Suppose we wanted to measure the pressure of the air in this room. There it is, pushing on the mercury on the left side, and there it is, pushing on the mercury on the other side. If we want to measure that full pressure, it won't be any good having it pushing on both sides. What must we do?

Elicit the suggestion of pumping the air away from one side. Bring out the vacuum pump, attach it to the mercury U-tube on one side and pump a little, and ask what is happening. Then pump some more. Then stop and raise the question of damaging the pump by pumping mercury up into the pump. By this time a healthy group of children

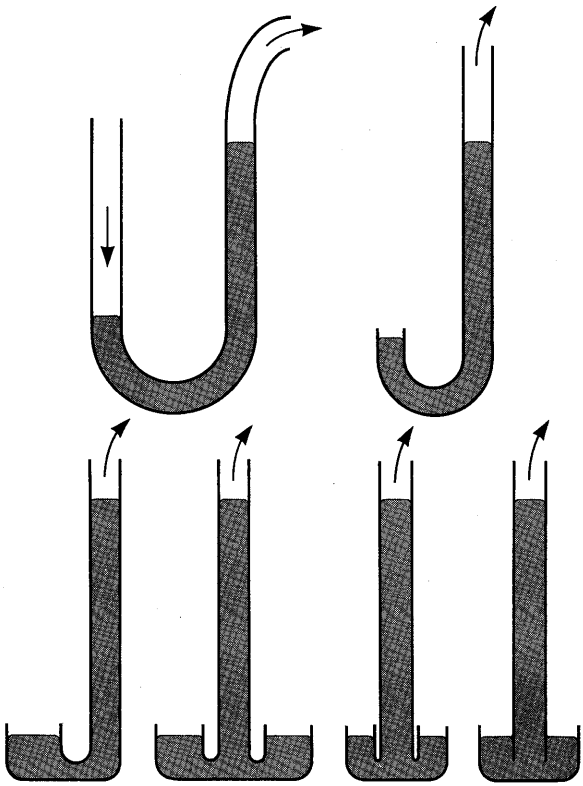


are frantic to see that happen. Go on pumping and show that there is a definite limit. Ask whether one can be sure that there is a good vacuum – 'just nothing' – on that side. Measure the level-difference of mercury.

Ask the children what it would be if we had used a water U-tube instead. (No need to give the answer: if they cannot work it out, they should do without for the present.)

NOTES

1. The pressure must be reached gradually by careful operation of the pump. This is made easier if there is a needle valve on the pump; alternatively a side tube can be used with rubber and a clip to provide a leak.
2. It is advisable to insert a trap between the pump and the tube to ensure that mercury does not enter the pump. This has the additional advantage of making it easier to evacuate slowly.



Barometer

Ask pupils if they would expect the same level-difference for a mercury U-tube with vacuum on one side if the U-tube had arms of unequal size, one made of much wider tubing than the other. Then draw a picture of several U-tubes: one with arms made of equal tubing; then one beside that with one arm made of much wider tubing; then another with one arm very wide; and then turn the very wide side into just an open dish.

45a Demonstration

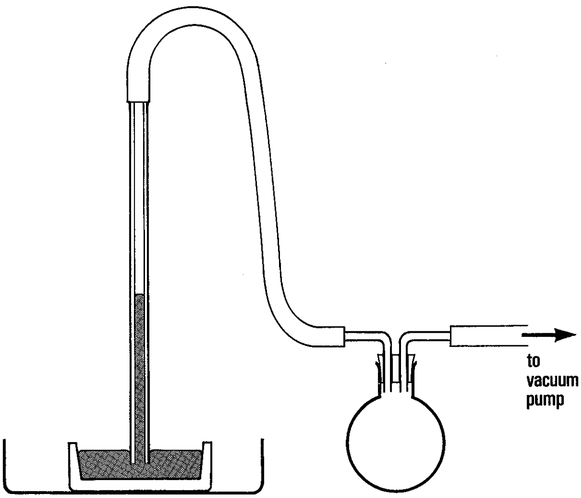
A barometer

APPARATUS *item no.*

1 Glass tube (1.2 m long, 4 mm bore, 8 mm ext. dia.) *6J*
1 Trough for mercury *6K*
1 Length of pressure tubing *10DD*
1 Retort stand, boss and clamp *503–506*
1 Vacuum pump *13*
1 Translucent screen and lamp *46/1 and 46/2*
1 Mercury tray *524*

PROCEDURE

Point out that a glass tube dipping in an open dish of mercury *is* a U-tube with one arm very wide indeed, and show that. Dip a tall glass tube, 1.2 m high, in a pool of mercury in an open dish. Connect a rubber tube to the top of that glass tube, and



pump the air out of it. 'Watch the mercury go up. What makes it go? Why does it stop?'

45b Demonstration

The simple barometer *(Optional)*

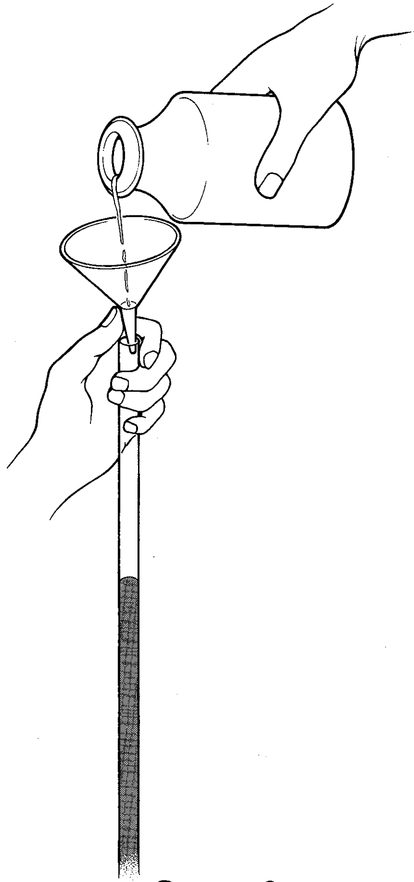
Those who wish may make up a simple barometer and demonstrate the tilting of the tube with that, taking, of course, all necessary safety precautions when handling the mercury.

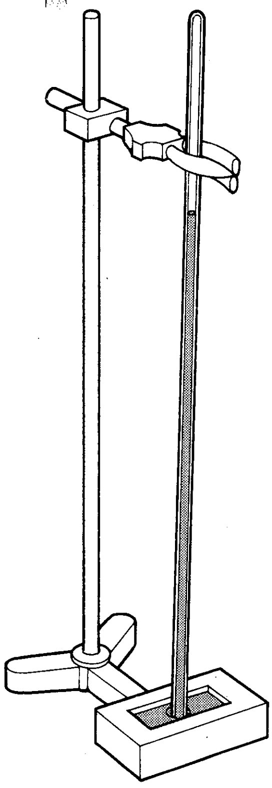
APPARATUS *item no.*

1 Barometer tube *61*
1 Bottle of mercury *535*
1 Small funnel *6L*
1 Trough for mercury *6K*
1 Mercury tray *524*
1 Retort stand, boss and clamp *503–506*
1 Translucent screen and lamp *46/1 and 46/2*

PROCEDURE

Fill the barometer tube with mercury, holding it over the tray throughout. (An easy technique for this is to pour mercury into the tube, using the funnel and a 5-cm length of rubber tubing, until it is nearly full, all but a centimetre at the open end.





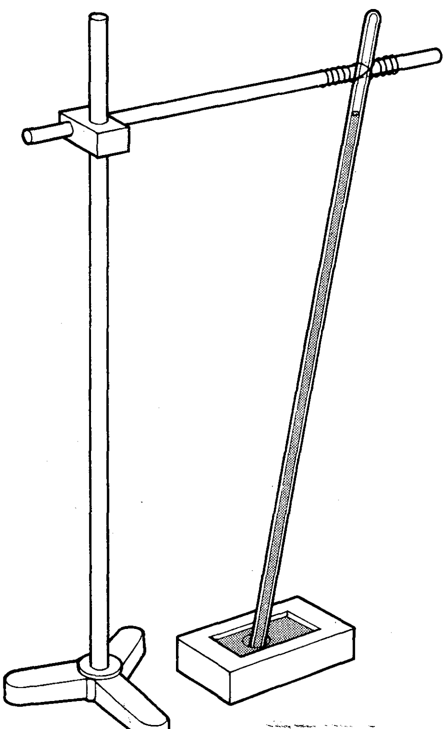
Close that end with a finger. Tilt the tube to run the air bubble very *slowly* to the other end of the tube and back again, collecting up any small sticking bubbles on the way. Then fill the tube to the top.)

Hold a finger on the top and invert into the trough. Do not remove the finger until the end of the tube is below the surface. Then ask pupils if air can get in. They should then watch what happens when the finger is taken away.

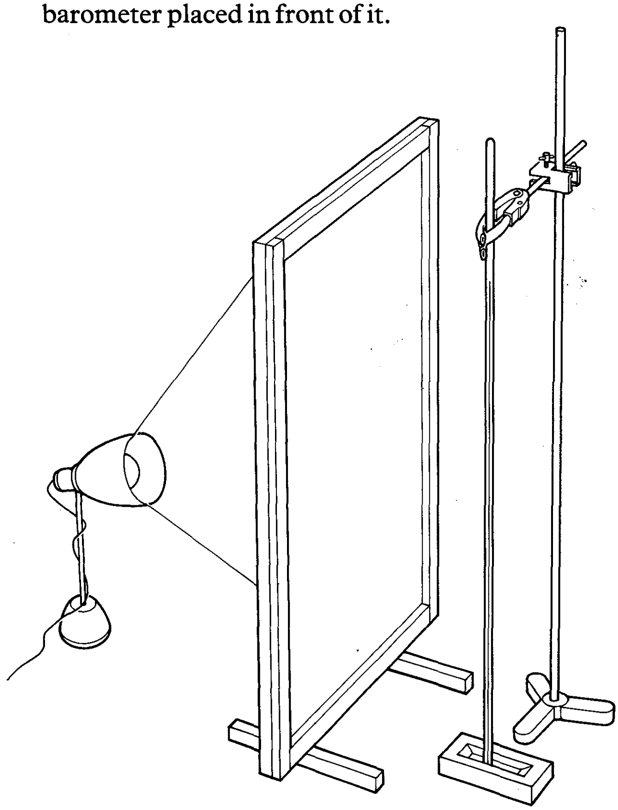
Hold the barometer in a clamp and measure the height.

Now we have a barometer which measures the pressure of the atmosphere in 'centimetres of mercury'.

Measure the height of the mercury column. Ask what happens if the barometer tube is tilted a little to one side. Try that.



Use of 'Translux' screen In these demonstrations, as in the case of mercury U-tubes, it is much easier for pupils to see the mercury, and even to make measurements accurately, if the tube is placed in front of a lighted sheet of translucent material. Teachers should have, for many experiments of this kind, some illuminated background sheets. Architects' tracing-linen is a good material for those.‡ It should be mounted in a wooden frame and provided with a lamp behind to give a brightly lighted surface which silhouettes the barometer placed in front of it.



45c Demonstration

The water barometer *(Optional extra)*

APPARATUS *item no.*

1 12-m length clear p.v.c. tubing
1 Bucket *533*
1 Vacuum pump *13*

PROCEDURE

Where schools have tall (10 m or more) teaching blocks and a suitable length (12 m) of clear p.v.c. tubing it is possible to set up a water barometer. The tube dips into a bucket of water at the lower end and is marked with coloured tapes at 50-cm

‡ This material scatters transmitted light over a *wide* angle; and that makes it specially suitable for this use – and specially unsuitable for viewing interference fringes, etc., from behind. For the latter, a very small angle of scatter is needed, so that enough light goes to the observing pupil directly behind the screen. Greaseproof paper, ordinary paper treated with oil, or ground glass, is best for that latter use.

intervals. The upper end is connected to the vacuum pump (preferably with the gas-ballast valve open) and the air is gently pumped out.

Alternatively, the tube may be coiled into the bucket and when full of water one end is corked securely. This end is then carried carefully to the top of the building leaving the other end in the water.

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46 Demonstration

What air pressure can do

APPARATUS *item no.*

1 Tin with bung and tubing
1 Length of pressure tubing *10DD*
1 12-cm bell jar *521*
1 Vacuum pump *13*
1 Large balloon
1 Small balloon
1 Thin sheet of glass (15 × 15 cm)
1 Thick sheet of glass (15 × 15 cm) *10W*
1 Tube vacuum grease *10X*
2 Safety sheets of 5-mm Perspex (one 75 × 75 cm, one 90 × 60 cm)

PROCEDURE

Show the strength of atmospheric pressure with some demonstrations, such as:

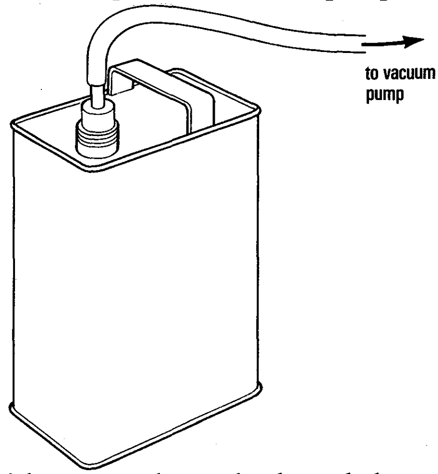
a. pumping air out of a tin can or a hollow rubber toy;

b. pumping air out of a bottle with a rubber sheet across its mouth;

c. pumping air out of a bottle with a partially inflated balloon in it;

d. pumping air out of a bottle with its mouth covered by a sheet of glass weak enough to crack.‡

a. The tin can – rectangular, not cylindrical and preferably litre size or larger – should have a well-fitting bung in the top with a short length of glass or brass tubing through it. This is connected by pressure tubing to the vacuum pump. The air



should be pumped out slowly and the can will collapse. Instead, or as well, a polythene bottle or a hollow rubber toy is pumped out.

Alternatively, a rectangular can has the bottom filled with water to a depth of about 1 cm. It is put over a Bunsen burner or gas ring and the water is boiled vigorously for at least two minutes so that the steam drives out all the air. Turn out the gas

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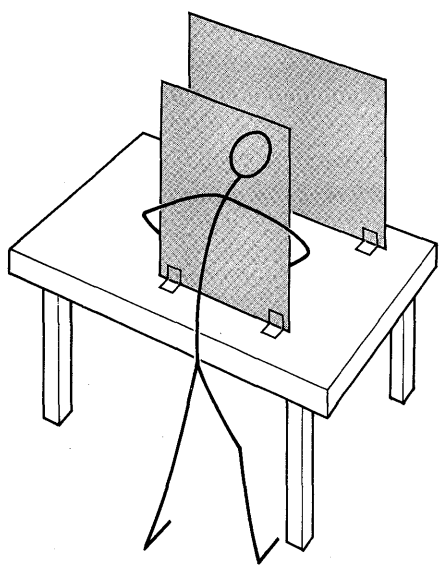
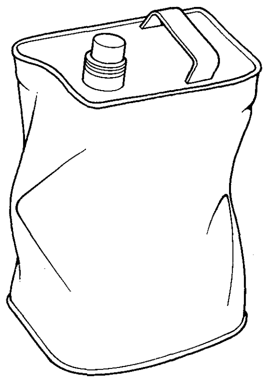
‡ This cracking of a sheet of glass is an impressive demonstration; but it is dangerous unless done with proper precautions. Very thin glass, which would make the demonstration easier and safer, is difficult to obtain. Therefore we suggest that if the teacher shows this at all, he should use ordinary window glass with the following precautions:
(1) Use a bell jar which has a neck at the rounded end with stopper and tube to connect to the pump. Place the sheet of glass across the open end of the bell and hold the bell with that end downward, very close to the table. (2) Place a large sheet of Perspex between the class and the bell jar, and another fairly large sheet between the bell jar and the teacher. Then operate the pump.

Those 'safety sheets' of Perspex form an important safeguard to be used again and again in our programme. The sheet for the class should be 75 cm × 75 cm. The sheet for the teacher should be 90 cm high × 60 cm wide – tall enough to protect his face but narrow enough to enable him to get his hands round comfortably from behind.

If these precautions are taken as a matter of course, without much talk about danger, an experiment like the one suggested here will prove valuable. But if either teacher or class invests the experiment with an air of worry about safety, it is better to get rid of the experiment – interest and care should be the watchword in science, not anxiety.



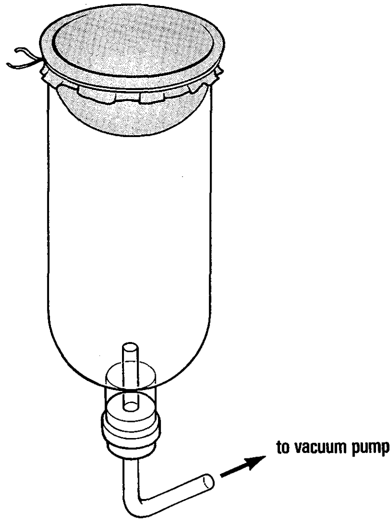
flame, or remove the can from it, holding it with a duster or oven cloth. After that, cork the can tightly. Allow it to cool and the tin will collapse under atmospheric pressure as the steam inside condenses. The condensation can be speeded up by pouring cold water over the can.



If pupils wish to try this as a home experiment, they should be warned that most small cylindrical cans withstand atmospheric pressure, so a rectangular can should be used.

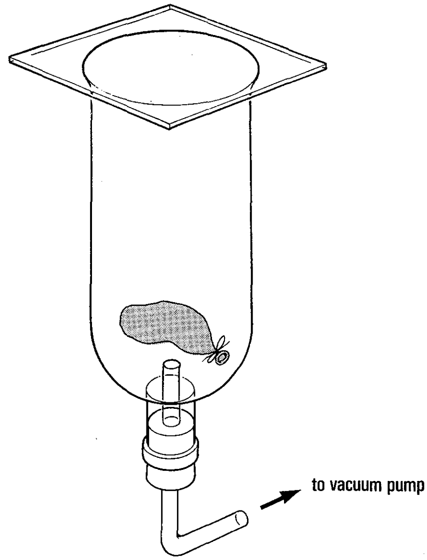
This can be a most spectacular demonstration done by the teacher with a large oil drum.

b. The outlet of the inverted bell jar should have a well-fitting rubber bung with a glass tube through it. This is connected by pressure tubing to the



vacuum pump. A part of a large rubber balloon, obtained by cutting off the neck, can be stretched across the top of the bell jar, being held on by its own tension. Air should be pumped out slowly to show the effect on the rubber sheet.

c. Close the bell jar with a thick glass sheet (using some vacuum grease to seal it) with a partially



inflated balloon inside it. Or this can be as effectively done by putting the partially inflated balloon inside a bottle connected to the pump.

d. Replace the balloon by a very thin sheet of glass over the bell jar. Air should then be pumped out of the bell jar very slowly indeed so that the breaking of the glass can be seen. The glass, which must be very thin, should be sealed to the rim of the bell jar with vacuum grease. A crumpled sheet of paper should be placed in the bottom of the bell jar to prevent glass chips reaching the pump.

Pressure in different directions

It is difficult to twist a mercury barometer around to show that the atmosphere pushes in all directions, always perpendicular to any surface it is offered; but we can show that with water. Encourage pupils to try the experiments suggested below – in class and at home.

These simple experiments should be done with old tin cans, not with some specially prepared gadget manufactured by suppliers 'to demonstrate water pressure' or devised by the teacher for clear working and easy storage. The intention here is to show pupils that we can still extract good knowledge from simple experiments with common equipment; and to offer them experiments – and arguments – that they in turn can give to people at home. Therefore old tins, such as a soup tin or even a large syrup tin, are essential, even if gathering a stock of them is difficult in this age of glass and plastic containers.

47 Class Experiment

Which way does pressure act?

APPARATUS *item no.*

16 600-cm^3 beakers *512/3*
48 Small beakers or tea-cups *512/1 or 512/2*
48 Tin cans
Hammers
4-cm round nails

The tin cans should preferably be about half-litre size and can be obtained from home.

PROCEDURE

For the success of the experiment, the holes punched in the tin must all be of the same size, very closely. We suggest that the child should punch the holes by driving a French nail through the can with a hammer. In careful hands a round French nail will produce much the same size of hole every time; but a careless bash will make a different hole. Therefore the teacher should point out the need for holes all the same size and give children a hint about making them and even some practical help. A block of wood, placed as an anvil inside the can, is a considerable help. (A block held in a carpenter's vice, with the tin can slipped over it, works very well – but there we have fallen into the error of devising special schemes.)

If making uniform holes proves difficult, the child should make them and then test them by slipping the nail into them again. He should replace abnormal holes by making another – stopping up the rejected holes with tape. The experiments are really simple, and such elaborations are usually unnecessary – it is more a matter of the temper of the class than of any real difficulty.

(The experiments are messy when carried out by young pupils. Teachers should decide whether they are prepared to deal with a considerable amount of water splashing in all directions.)

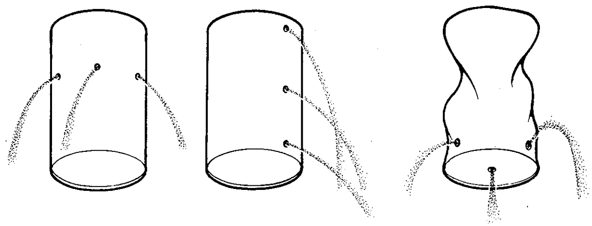
Pupils follow these instructions:

* * * * *

a. Take a tin can and make some holes in it with a round French nail. Try to make all the holes exactly the same size. (If you like, put a piece of wood inside the tin as a backing, and then hammer the nail through the tin into the wood.)

For your first experiment make several holes at different places round the can all at the same level, about half-way up from the bottom. Fill the can with water and hold it up and watch how the water spouts out from the holes.

Does it spout out equally well from all the



holes? If not, do you think you have made all the holes exactly the same size? If you want to make a more scientific test, catch the water that spouts out in separate beakers or teacups, one for each stream of water. How can you tell from that whether you made equal holes?

b. Take another tin can (or block up the holes in the one you used) and make three holes, one hole near the top of the can, one part-way down, one near the bottom. Now fill the can with water again and watch how the water spouts out.‡

c. Take another tin can, batter it to an irregular shape with a hammer, and drive a French nail into the battered bottom at three different places all near the bottom, where the metal surface is in three different directions.

One hole may be in the bottom of the can, so that the water spouts out of it straight down; one hole may be in the upright side of the can, very near the bottom, so that the water spouts out horizontally; and one hole should be in a tilted direction, in a part of the can very near the bottom, that you have bashed with a hammer. Make sure that the three nail-holes are all the same size.

1. In what direction will the pressure make the water spout out when you fill the can up? Try it.
2. How fast will the pressure make the water spout out of the different holes? Try that (keeping the can topped up with water as the water spouts out, if you like). You may collect the water spouting out from the three holes in three separate beakers or teacups.

‡ Teachers will note that this is a traditional paradox problem. Asked to sketch the jets of water from those three holes, a physicist is likely to predict a progression of ranges: the jet from the top hole reaching the table nearest the can, the jet from the middle hole arriving farther out, and the jet from the lowest hole, with biggest pressure, spouting farthest.

Then a thought experiment warns him that this must be wrong: if the can rests on the ground, water from a hole at the very top (the free surface) will dribble down the side and arrive at the very edge of the can; and water from the very bottom, however fast it spouts out, will also hit the ground immediately, just at the bottom of the can. Yet water from some intermediate level will spout out and arrive some distance away.

Finding the full story is a short interesting calculation, easy for a sixth-form pupil.

Watch what happens; be a good detective and squeeze any information you can out of the clues that you observe.

* * * * *

As a suggestion for an experiment at home, ask pupils to fill a balloon with water and make holes in it with a pin. This is an exciting, messy, experiment which does not usually yield any very clear result. For scientific knowledge, repeating the experiments (*a*), (*b*), (*c*) above is better.

Invite the children to apply this newly won knowledge about pressure and the way that it acts in all direction to the experiments which showed the forces which the atmosphere can produce (Demonstration 46 above).

There is scope for further work on the atmosphere, possibly in conjunction with the geography department; at least visual material and books should be available to those who are interested.

A thought experiment concerning the atmosphere This is an argument, a taste of theory – thinking that is fantastic and unreal but yet of help in building our knowledge or understanding – difficult but within the compass of some of these pupils.

Remember the question about living in an atmosphere of mercury. How high would the mercury have to be from the floor to the top of the atmosphere if that was all there was to make the pressure that we actually live in? . . . Yes, the height would have to be the barometer height, about 75 cm of mercury. Now think about the real atmosphere. How high would that have to be if it went on up and up just as thick as the air is in this room, and then stopped suddenly at the top, and there was nothing more above?

Well, how high would it have to be if it were all made of mercury? We asked that before. . . . Yes, the same height as the mercury barometer height. Because that is the height of mercury which can press on the base of anything with the same pressure as the whole atmosphere. The atmosphere pressing on one side, on the open pool, balanced the mercury on the other side in the barometer, with only a vacuum above it. So the *mercury* atmosphere would have to be about 75 cm high.

How high would a *water* atmosphere have to be? Remember, the water is not so dense as mercury. Mercury is $13\frac{1}{2}$ times as dense as water, so, a water atmosphere would have $13\frac{1}{2}$ times the mercury height; $13\frac{1}{2} \times 75$ cm, about 10 m.

Now what about an atmosphere of *air* – not air that gets thinner and thinner all the way up, but air that stays just as it is here, in this room?

This brings us back to the early estimate of the density of air. (If that was not done before, or not well understood, now is the time for it, but it would be better to do it earlier and now pick it up and use it – because that shows physics as a connected structure which uses one thing several times.) We have to find how the density of air compares with the density of mercury.

Density measurements show that air has a density about 1.2 g per litre. Mercury has a density 13 600 g per litre. Arithmetic gives from that a density ratio of about 11 300 to 1. Therefore if we had a uniform atmosphere of air, it would have to be $11\,300 \times 0.75$ m high; or somewhere about 8.5 km.

(We must warn the children, if we carry them through this story, that the real atmosphere gets thinner and thinner as we go higher and higher, so the story we are telling is an artificial, simplified one in order to arrive at an interesting guess.) Then we ask the important question:

Suppose air is made up of little molecules, tiny things far apart; then one of them, which happens to be at the very top of the atmosphere all alone, would start to fall faster and faster and faster, like anything else that falls. It would not flutter down like a sheet of paper, fluttering against air resistance, because it is just a molecule of air itself falling through spaces between other molecules. Then it would be moving very fast indeed when it reached the ground and bounced against the floor, or the top of your shoe, or anything like that. No wonder it makes a big pressure.

Scientists think of air molecules as moving about very fast like that and bouncing off everything they meet and making the pressure of air that way.

This simplified story of air molecules moving up and down and rising to the top of an artificial atmosphere, coming to rest and dropping down faster and faster again, is not as queer and useless as it sounds; a full version of that was used by Boltzmann to do an important calculation, a derivation of the Maxwell distribution of gas molecules' velocities. We too could do a very interesting calculation with this at a later stage when our pupils can calculate the speed which a freely falling object would have after falling, say, 8 km; they can obtain a rough estimate of the speed of air molecules. Treating this as a case of free fall, we obtain a speed of over 400 m per second, compared with the 490 m per second that a proper calculation yields.

MODEL OF A GAS

Are air molecules really in constant motion?

Scientists think of air molecules as moving about very fast and bouncing off everything they meet. That is not just a wild guess; though molecules are too small to see, we can see their actual effects. Look at some tiny specks of ash floating in air. You can get those by putting a little smoke in a small round box under a microscope.

Watch the tiny specks and you will see them dancing about. You cannot see the air molecules but you can see that something is jostling these much bigger specks.

Imagine that players in a football game were invisible, too small to see. But suppose a visible elephant on roller skates could be parked in the middle of the football field during a game. You would notice the elephant moving in a most irregular jumpy way, as he was pushed around by collisions with players. That is the kind of thing that we think is happening to the bits of ash you are going to watch. But first you should look at a model of molecules, the tiny particles, in a gas.

Note on models Models are very important: they form essential links between experiment and theory. They are also very dangerous, because pupils tend to take them too literally. In fact that danger applies to all of us. Consider how medieval astronomers took the planetary crystal spheres literally. Or note how clear-cut electron orbits survive from the Bohr atom model.

We should introduce models and use them freely at every stage of our teaching. In early stages we need not issue grave warnings about something being 'only a model' and we certainly should not enter into long discussions of the nature and use of models. We say lightly

'... may be something like...'

'let's pretend that...'

'you may picture... as rather like...'

'Here is a machine to show the kind of thing we are talking about...'

'not real . . . but only a toy to help you think about it.'

In later years we should describe models more emphatically as imaginary schemes, ideals, metaphors, analogues; and we should emphasize their great uses in constructing a fabric of scientific knowledge.

In discussing our teaching use of models with professional physicists we shall meet some critics who object that mathematics makes models unnecessary in advanced physics. We might point out that mathematical forms and equations *are* models. They are not full, true samples of Nature: they are powerful, clear thinking-schemes to help us express our views of Nature. For example, $\ddot{x}+n^2x = 0$ is a purified model of simple harmonic motion; but we need a pendulum or a loaded spring to experience simple harmonic motion in Nature – and, as physicists, we know their limitations in contrast with the 'unlimited' mathematical model. Extend that use of mathematics, and we have our modern descriptions of atoms, in models that seem almost entirely mathematical.

48 Class Experiment

Model of gas molecules in motion

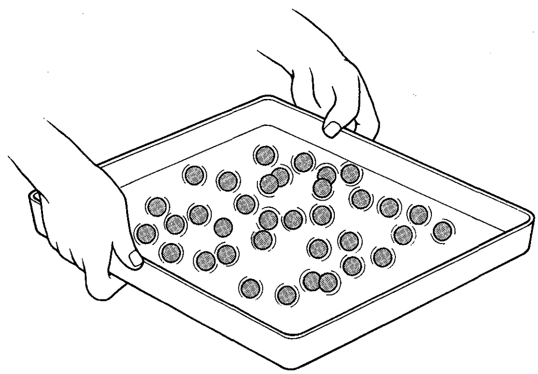
APPARATUS *item no.*

1 Two-dimensional kinetic model kit *12*

The kit includes 16 metal trays enabling pupils to work in pairs. Each pair requires some 20–25 coloured marbles–these are included in the kit and are the standard size of toy-shop coloured marble, about 16 mm in diameter.

PROCEDURE

The tray should be of metal (or glass) with massive *vertical* edges, with two dozen ordinary glass marbles in it. The pupil operating it keeps the tray on the table and moves it with a rapid, jerky, vibrating motion. A circular motion will do if it is interrupted by frequent changes. The noise is



reduced if a thin sheet of cork is placed in the tray as a carpet; and then pupils can hear the individual collisions of 'molecules' with walls and with each other; and can distinguish between those two kinds of collision by ear.

Pupils may ask why we have to keep agitating the tray, when a real gas does not require a continual supply of energy to the walls of its container; and when that question arises we should say that the walls of all containers are, on a molecular scale, themselves in constant agitation. If pupils distinguish by ear impacts on the sides of the tray from collisions between one marble and another, they can listen to the pressure increasing as the sound of the former grows.

Uses of two-dimensional model in Years 1 to 4 Although only two-dimensional, this model simulates the behaviour of gas molecules more closely than some three-dimensional ones. By choosing the colours of marbles so that there is only one marble of some prominent colour, say red, pupils can watch the progress of that marked marble through the crowd. They can see its slow progress (diffusion) and many different velocities. They can visualize mean free path. They can change the 'temperature' of the collection.

More marbles can be added to the tray to suggest increase of pressure with density. Marbles can be crowded into one half of the tray with a ruler; and then, with the ruler removed, we can see the 'gas' expand to fill the tray – and we may ask a very able group a thermodynamic question, 'Is the expanded arrangement ever likely to go back to the crowded one of its own accord?'

Pupils may add more marbles until they have something nearer to a liquid. Or they may tilt the tray to form a model of liquid and vapour. All these are extensions of the simple experiments that we suggest here. They should not be tried now; but the tray should be used again and again in the following years; and it will even find an important place in Year 4.

At present, we simply give a tray and marbles to each group of children and ask them to agitate the tray and watch what happens.

This is such a simple but powerful model that we hope some children will make their own version at home. They need a tray whose edges will bounce a marble back easily. A bright 'tin' baking tray, about 30 cm × 20 cm with edges 12 mm to 20 mm high, does well, provided the sides are *vertical*. Most ironmongers stock trays with sides that slope outward (and marbles do not rebound well from them) but from time to time a line of trays appears with vertical sides. A packet of glass marbles from a toyshop is the only other thing that is needed.

49 Class Experiment

Adding a larger marble: a model for Brownian motion

APPARATUS *item no.*

1 Two-dimensional kinetic model kit *12*

In addition to the standard coloured marbles in the kit, there is also a supply of large coloured marbles (about 25 mm in diameter), and these are needed for this experiment.

PROCEDURE

After Experiment 48, one or two larger marbles should be added to the collection in each tray. Ask the children to agitate the trays again and to watch the larger marbles. This experiment will be recalled when they see the motion of the smoke-ash particles in air and may well be shown again after that experiment (Experiment 51).

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50 Demonstration

Another model of gas molecules – in three dimensions

APPARATUS *item no.*

1 Three-dimensional kinetic model kit *11*
1 Fractional horse-power motor *150*
1 L.T. variable voltage supply *59*
1 Retort stand, boss and clamp *503–506*

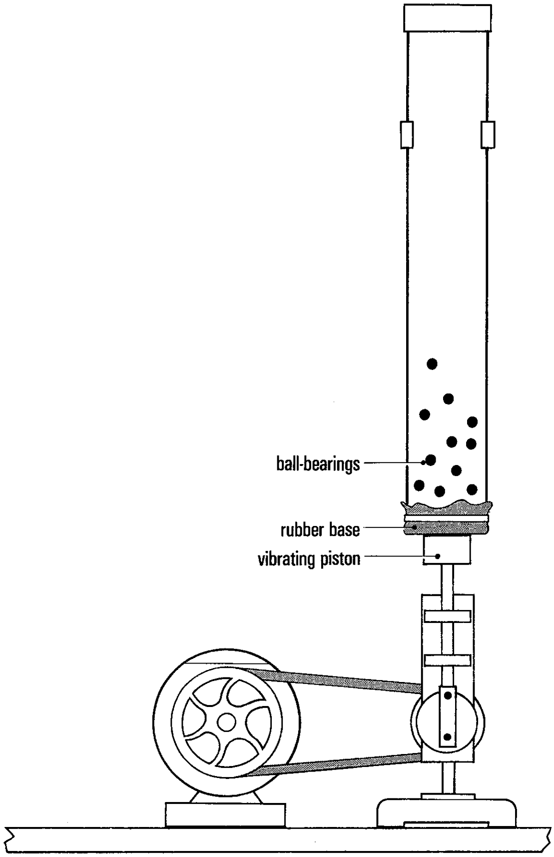
As an alternative to the fractional horse-power motor, the motor from the Energy Conversions kit (item 9A) will be found convenient.

PROCEDURE

The rubber base is fixed over the lower end of the plastic tube, which is held in a vertical position using a retort stand, boss and clamp.

The height of the tube is adjusted so that the rubber is a millimetre or two above the vibrating rod in its mean position. The motor is used for activating the vibrating rod. The d.c. terminals of the L.T. variable voltage supply are connected in parallel to the field and armature terminals of motor item 150, or directly to the terminals of motor item 9A. The small phosphor-bronze ball-bearings are put inside the long tube so that they rest on the bottom. The most effective number will cover about two-thirds of the base area. The brass cap should be put over the top of the tube: it stops balls from coming out and cuts down noise.

When the voltage is increased, the vibrator is set in motion and we have a simulated kinetic theory motion. Start with a low voltage, and gradually increase it, showing the action of the



balls increasing. Take care not to exceed the appropriate maximum.

The distribution of 'gas molecules' will probably excite comment: the 'atmosphere' is visibly thinner higher up. We should say at once that that is a very good model of our real atmosphere.

Again, this model can be changed to show the Brownian motion by adding a larger ball among the 'gas molecules'. For a close model, the Brownian-motion particles should be much more massive than the small 'molecules'. However, in practice it is better to use a very light but large ball because then the small balls provide enough buoyancy to keep it from falling down.

(Like the two-dimensional model, this model will be used again and again, to illustrate further aspects of gas behaviour, in Years 2, 3, and 4. Therefore we need not go into much detail now.)

Brownian motion: class experiment

This is one of the most important 'atomic' experiments in the whole course: it is one of the few that show the 'graininess' of Nature – molecules, atoms, electron charges, quanta of energy. The children should have plenty of time to see it, and a good chance to see it again if they wish. The microscopes that were needed for Experiment 1a should be brought out again so that children can see the real Brownian motion for themselves. As we explained in discussing that earlier use of microscopes, many biology departments feel that they should not lend their best microscopes for class use with these young pupils. And in that case it is essential for a school following our programme to buy enough microscopes (simple models but with large enough aperture) for that general use, and for this use for the Brownian motion. There should be one microscope for every four pupils. (The Nuffield Biology project asks for microscope – one for every four children – and if that programme is being used in the school, those microscopes would serve well.)

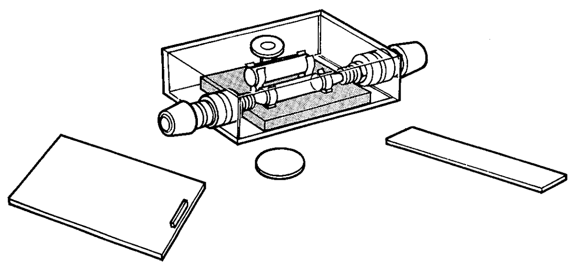
The motion of particles in water will *not* suffice as a substitute. The experiment with smoke particles is much easier to see than the more usual one with a suspension of carbon or other small particles in water. With smoke, a low-power objective is needed, whereas the water suspension needs a high power, preferably used as a 'water-immersion' lens. Besides, we are talking about gases and suddenly to show water instead seems puzzling.

51 Class Experiment
Looking at smoke particles

APPARATUS *item no.*

8 Microscopes *23*
8 Whitley Bay smoke cells *29*
8 Transformers *27*

Microscopes with fairly low power but large apertures are required. It is imperative that there be sufficient clearance between the stage and the objective to take the Whitley Bay smoke cells. The focal length of the objective should be between 10 and 30 mm, preferably about 18 mm, which is one of the standard values. A × 10 eyepiece should be used.



PROCEDURE

Remove the plastic cover from the smoke cell assembly and place on the microscope stage. Connect 12 volts from the transformer to the terminals provided on the smoke cell.

Light the end of a piece of cord (sash cord, clothes line or a drinking straw are suitable) and allow to burn for a few seconds. Blow out the flame and fill an eye-dropper with smoke from the smouldering cord. Inject the smoke slowly from the dropper into the glass cell. When it is full, seal with the cover slip provided.

Focus the microscope on to the top of the cover slip and then slowly lower the objective until the Brownian motion of the smoke particles becomes apparent. Where a small piece of black material is provided with the cell, this should be placed over the festoon lamp to avoid stray light reaching the eye. In other cases, the plastic cover is opaque and serves as a light shield.

This is one of the most crucial experiments in the whole course and should not be sacrificed or rushed. Pupils need a considerable time to look into a microscope and decide what they are seeing. We must be patient and arrange for plenty of time, so that each child has adequate time with the microscope.

Again show the models of gas molecules, with a large 'particle' added to simulate Brownian motion. (The three-dimensional model and the tray with marbles.) Point out that molecules of air must be much smaller than the smoke particles. Again raise the question of the size of molecules. We shall ask pupils to do an experiment to estimate the size of a molecule later.

Note on arranging the Brownian motion experiment As with the class experiment of pupils using microscopes to look at things, teachers may feel tempted to arrange things so that pupils can take turns to look at the Brownian motion with a single microscope, or perhaps two, under their supervision. This is very tempting – and even more strongly tempting when one has tried keeping eight microscopes and smoke cells going – but we hope that teachers will not do that. We hope they will have the patience and courage to keep this as a class experiment with, at most, four pupils per microscope – even if that is at the expense of spending several periods on it. This and the oil film will be pupils' only direct contacts with truly 'atomic' experiments for many a year, and each child deserves to feel that he has really looked at the motion of smoke specks through his own microscope. Even if a demonstration or a carefully organized queue seems to work as well, it will not have the same value in long-term memory.

Therefore it is important to have smoke cells with an illumination arrangement that shows the particles brightly, even with a small microscope, and does not give too much convection. The lamp must be attached to the microscope so that when a child moves the microscope the illumination is not cut off. The position of the lamp and the focusing of the microscope must be arranged so that the smoke that is viewed is almost at the top of the cell, so that convection is less pronounced. (When children look at smoke specks in the small cell there are two difficulties: (1) There may be convection currents. There will always be slow drifting; but if there are strong convection currents so that the whole collection of smoke specks sweeps across the field of view, something is wrong, either with the illumination or with the box, which *must be tightly closed.* Those currents will confuse the story for the children badly and we must stop them. (2) There will always be some specks out of focus, and others which are in focus at one instant will dance out of focus the next. Specks which are out of focus appear as round patches of light; children need to be warned of this. The working of the smoke cell takes some apprenticeship and many a teacher uses it for some time without knowing its full possibilities. It is a thing to play with carefully beforehand and to watch while pupils are using it.)

The glass cell can be removed from the assembly and cleaned. It must be pushed fully back into the assembly and it may help to do this by wetting the outside of the glass tube. It will be found helpful to clean the glass cell after every five to ten fillings to obtain the best results, otherwise the light intensity is reduced.

How small are molecules?

The Brownian motion tells us that air molecules are smaller than the smallest specks of smoke we see. How much smaller? We know from chemical experiments that molecules of air are pairs of atoms, so atoms must be a bit smaller still. How small are atoms? Try making a wild guess at the number of atoms that you could park in a row, side by side, all along the length of a postcard – this length between my fingers. You can't possibly tell yet; but make a guess for fun, and write it in the back of your notebook.

This is a first chance to give the idea of 'order of magnitude', not by that name, but by asking children whether they think the length of a postcard would contain 100 atoms in line; or 1000; or 10 000; or 100 000; or . . . and point out the good sense of skipping up by a factor of 10 each time and not bothering for greater precision until we get some idea of which county we are in.

The police are hunting for a robber. They want to know which house he is in, not which chair he is sitting on, in which room, on which floor of some house in a street. Scientists are professional detectives finding out about Nature. In thinking about their work and telling each other about their work they first give rough answers.

For example, in chemistry we sort out all the materials we know into atoms of one kind and atoms of another kind and so on. We say that atoms all-of-one-kind belong to an 'element'. If there were 10 000 different elements making up this world, chemistry would be so complicated that we should never have sorted it out, even yet. If there were only 10 kinds of atom, only 10 elements, chemistry would be far simpler than it really is. There are in fact about 100 elements. But from the point of view of knowing whether chemistry is going to be very difficult or not, all we need to know is whether there are 10 elements, 100 elements or 1000 elements.

This is not a good example. It is given here only as a sample of the kind of story which a teacher should devise to illustrate the value of rough estimates.‡

Some parts of Questions 62 to 65 in Chapter 1 of the *Pupils' Text* will be useful here.

Although a rough guess would be sensible for the question about atoms along a postcard, you still need to know something about the size of atoms before you can make any estimate. You can tell that atoms must be very small by using common sense.

Suppose atoms were great big things, so that we had only a few of them in a teacup of water. If they were big enough to see you would certainly notice them; and you might even hear them. Suppose atoms were as big as these marbles; listen . . . .

Atoms must be very, very small. And molecules, which are the small groups of atoms of which each chemical substance is made, must be very small too.

52 Demonstration
Pouring peas

APPARATUS *item no.*

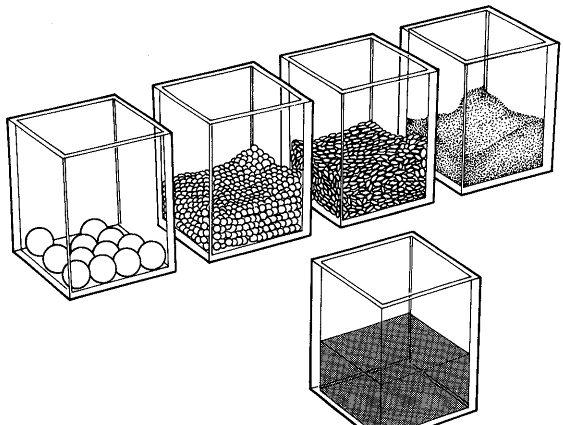
5 Perspex containers *26*

One container should be empty, the others three-quarters full, respectively, with marbles, dried peas, sand and water.

Plastic containers are used as the marbles might break a glass beaker when poured into it.

PROCEDURE

Pour a handful of marbles from one transparent container into another; then a handful of dried peas; then a handful of sand; then a handful of water, pouring the water very smoothly.



At this point some teachers like to give a demonstration of purple dye in water being diluted more and more and more, being visible as a uniform pink colouring to a very late stage of dilution. In the nineteenth century that was used as a desperate attempt to set an upper limit to the size of molecules. If molecules were large – if the graininess of matter were coarse – a sufficient number of diluting stages would produce a liquid in which patches or specks of pink could be seen instead of the uniform colouring. The experiment was pushed to the limit where the pink colour became invisible in a thin layer; no patches were seen.

This, therefore, did *not* demonstrate the existence of molecules or atoms as limiting particles of dye. It only showed that *if* molecules do exist, then they must be extremely small and therefore extremely numerous – so numerous that even in the utmost dilution there were far too many of

‡ The planning of a safari might be a suitable example:
If it is to be about 10 km, all we need is stout boots.
If it is to be about 100 km, we need some food and a tent.
If it is to be about 1000 km, we will need porters to carry all the equipment.
Or the planning of alterations to our house:
If the alterations are going to cost about £10 we get someone to do it straight away.
If the alterations are going to cost about £100 we ask for estimates.
If the alterations are going to cost about £1000 we consider very carefully whether we can afford it at all.

them to show irregularities of pink patches. It was useful then in showing one must look for smaller sizes, if there are atoms. Now that we know so much about atoms, and can make good measurements, that experiment is only of historical interest – unless we can use it with very careful logic.

Teachers who have shown it and discussed it in our trials are almost unanimous in recommending we should omit it. It is a dangerous experiment because pupils so easily jump to the wrong conclusion and think that we have said: 'Now you know how small atoms are' – which is quite untrue – or, worse still: 'Now you have evidence for atoms'. In fact, this attempt ends so far short of real atomic sizes that it cannot possibly point to atoms.

CHAPTER 7

Measurement of a molecule

How oil spreads out over a sheet of water

Our next experiment is an estimate of the size of a molecule. Each child places a tiny drop of oil on a perfectly clean water surface. The child measures the size of the drop and the size of the oil patch. We show children how to work out an estimate of molecule length by a short-cut in arithmetic. This is an 'atomic measurement' that a child can take home with pride.

Can we measure atoms?

It would be wonderful if you and I could measure a single atom, measure its size just as you and I can measure the width of a boy's head. But atoms are really so small that we cannot do that directly. Yet I can show you how to find the size of a molecule by a roundabout way; and from that you can guess the size of an atom. We shall choose a molecule that is specially easy, a molecule of olive oil, which is a long chain about a dozen atoms long.

Chemists can find out how the atoms are arranged in the big oil molecule, even if they cannot find out the actual size of the molecule. Then, if they tell us the olive oil molecule is a dozen atoms long, we can find out the size of a single atom just by dividing by twelve, if only we can find out the length of that oil molecule.

You are going to be able to do that, by putting a tiny drop of oil on water and watching what it does on the top of the water. To understand that experiment you will need some experiments of your own first, on liquid surfaces. So we shall start with them and then come back to the question of the oil molecule and its size.

Note on the oil molecule measurement This measurement ranks very high in our experiments; and it should not be omitted or hurried or be allowed to become a demonstration. It provides opportunity for manual skill, careful imaginative thinking – for which models and pictures will help – and also for some appreciation of orders of magnitude, degree of accuracy, and approximation.

In this experiment, each child puts a very small measured drop of oil on a clean water surface and measures the size of patch to which the oil spreads. The original oil drop is measured by looking at it with a magnifying glass against a scale marked in half millimetres, and trying to adjust the oil drop to a diameter of $\frac{1}{2}$ mm. The patch to which the oil spreads is made visible by dusting the water surface beforehand with waterproof powder, such as lycopodium spores. The tray in which the water is held is painted black, so that the clear patch made by the oil shows black in contrast to the lighter powdered surface.

The patch is measured and its thickness calculated, assuming the volume of oil remains unchanged when the drop spreads to the patch. If, following Lord Rayleigh, we assume that the oil spreads until it is a layer one molecule high, we have an estimate of the length of an oil molecule.

In preparing for the experiment we try to build up enthusiasm for an atomic measurement, saying we are desperate for some idea of an atom's size and will be glad of even a rough value. The experiment is not done until children have seen something of surface tension and have been told something of oil molecules and water. But they should *not* see a specimen demonstration of the actual measurement.

Surface tension experiments

Some acquaintance with surface tension phenomena is needed as a preliminary; but, delightful as such experiments are for children, we should not spend long on them now, but should rather provide suggestions for more experiments that can be done at home – such as flat soap films with a loop and thread; stretching a film by pulling a thread; joining two soap bubbles together with a pipe 'to see the big bubble blow the little bubble up until they are equal'; putting a drop of water on a waterproof table and spoiling it with a detergent; waterproofing a sieve; wetting a waterproof greasy rag with wetting agent so that it can be dyed, etc.

53 Class Experiment
Looking at drops

APPARATUS *item no.*

16 Eye droppers *102*
16 Beakers (400 cm^3) *512/2*
32 Microscope slides *3G*
Paraffin wax *7S*

1 Bottle wetting agent
1 Bunsen burner *508*
1 5-cm soft paint brush *7R*
1 Can for heating wax *7T*

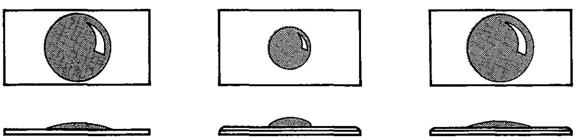
This demonstration is a poor one with ordinary detergents compared with the startling effect of a 'wetting agent' designed to act between wax and water. That recommended is Manoxol–OT, obtained as a powder from B.D.H.

PREPARATION OF GLASS SLIDES

One of the microscope slides must be clean, the other coated with clean paraffin wax. To coat the second slide, heat about 100 g of clean paraffin wax in a saucepan. When it has melted and is very hot (almost smoking) either dip the slide in the wax and let it drain or paint some of the liquid wax on the slide with a clean, cheap paint brush.

PROCEDURE

Working in pairs, the pupils should watch a drop of water being formed very slowly at the tip of the eye dropper and then falling into the beaker of water. They should be asked to sketch the growth of a drop.



Pupils should make a small pool of water on a clean slide, using fingers or an eye dropper, and then on the waterproof waxed slide. For the best effect the 'pools' should be about 12 mm in diameter.

The teacher should then produce the beaker of 'wetting agent' and let each pupil dip a match-stick in the solution, to try in the pool on the wax. This will spoil the waterproofing.

After use, the wetting agent must be removed from the waxed slide before it is put away. This is done either by copious rinsing or by removing the wax (which must be thrown away) and rewaxing with new wax.

These simple experiments give an idea of water surfaces behaving *as if* they had an elastic skin. We should make it clear that there is not a real skin that can be flayed off like a rabbit's.

If we give children the usual explanation of these effects by molecular attractions, we must be careful to describe also the outward forces on surface molecules, due to them being jostled by neighbours all round them inside. Both lots of forces are there, the short-range attractions of neighbours and the very short-range repulsions of collisions with neighbours. The surface molecules are in that way in equilibrium, but they are not in the same type of field of forces as molecules well inside the liquid, so their energy and their behaviour are different.

In a way these experiments which show surface *tension* do not seem directly relevant to the spreading of an oil film. Children should now try the more relevant experiments: the effect of adding various things to a clean water surface.

54 Experiment

Some experiments with liquids pupils could try at home

APPARATUS

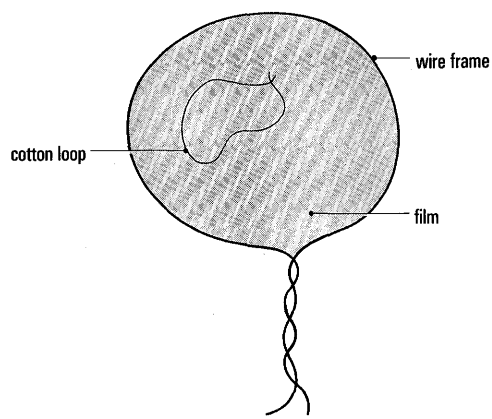
A little household detergent dissolved in water provides a useful substitute for the traditional soap solution in surface tension experiments. But where greasy materials are involved a weak solution of 'Manoxol–OT' is to be preferred.

PROCEDURE

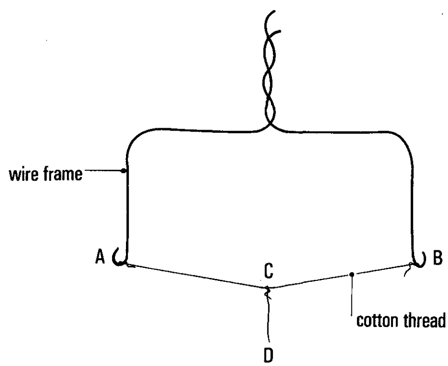
Pupils follow these instructions:

a. Soap film

Make a circular loop from about 30 cm of wire. Make a loop from about 10 cm of cotton. Dip the wire loop into the detergent solution and form a film. Drop the cotton loop on to the film and then touch the film within the cotton loop with a hot wire or a piece of chalk.



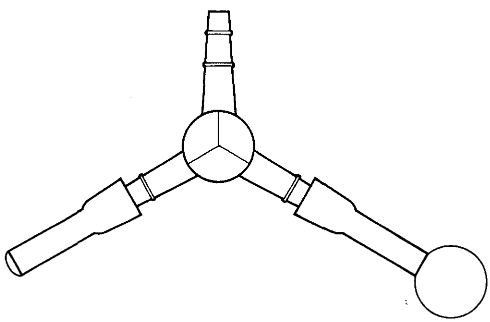
Alternatively, tie two pieces of cotton loosely across the diameter of the wire loop and break the film between them.



Make a square frame of wire and close its open side with a loose thread as shown. Tie a second thread to the centre of this loose thread. Form a film on the frame and try the effect of pulling on the loose thread.

b. Soap bubbles

Borrow a 'T' piece or 'Y' piece, and two short lengths of rubber tubing. Form a film over each end. Pinch the rubber on one end whilst you blow a large bubble on the other piece. Now watch one blow the other one up. Which is which?



c. A waterproof sieve

Make a small tray from perforated zinc. Dip it into molten candle grease. Will it float or hold water?

d. Quick dyeing

Take a greasy rag – and make up some dye from ink and water. Open the rag on a sloping sheet of glass and throw some dye over it. What happens? Now add a few drops of the Manoxol–OT solution to the dye and try again.

e. Pour some molten wax on to a scrap piece of wood to give a waterproof surface. Put a drop of water on the surface. Look carefully at it from the side, and touch it with a matchstick which has been dipped into your Manoxol–OT solution. What happens?

f. Float three matchsticks on some water, so that they form an equilateral triangle on the water. Touch the water between the matchsticks with the corner of a cake of soap. What happens?

Experiments to prepare for oil film

(These experiments might be done as demonstrations to save time; but as class experiments they have a much more personal impact. Children enjoy them, provided the cleaning process can be speeded up. If cleaning can be done beforehand, children should do all the following experiments.)

55 Class Experiment

Experiments with a water surface

APPARATUS *item no.*

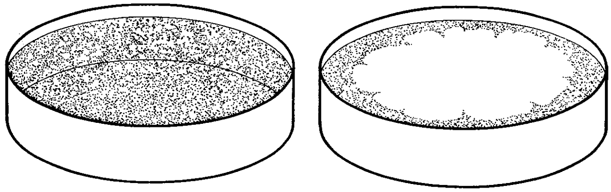
	Crystallizing dishes	*528*
8	Lycopodium powder dispensers	*7M*
1	Bottle of olive oil	*7H*
1	Bottle of alcohol	
	Crumbs of camphor	*7U*
16	Eye droppers	*10Z*
16	20-cm lengths 16 SWG iron wire	*10BB*
16	Bunsen burners	*508*
16	Heat-resistant mats	*509*
16	Heavy iron wires	
16	Beakers (400 cm^3)	*512/2*
	Detergent for cleaning	

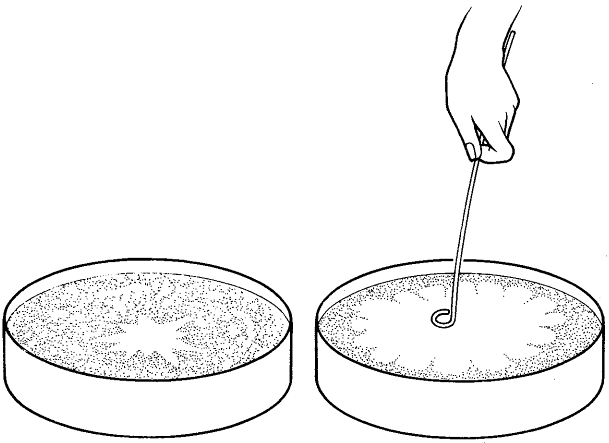
As the dishes become dirty quickly, it is advisable to have thirty-two, or even forty-eight, for a class.

PROCEDURE

Before the lesson begins, the dishes must be cleaned carefully as cleanliness is essential. They should be cleaned with a non-foaming and soda-free detergent (such as Dreft) and then carefully washed to remove all detergent.

a. The surface is very lightly dusted with lycopodium powder. Put a drop of alcohol on the powdered surface. A clean patch appears as the powder is pulled away to the edges (or 'pushed' by the alcohol). The powder returns as the alcohol dissolves in the water or evaporates. The dishes need to be very clean for this. (The teacher can test the cleaning of a dish by putting a drop of absolute alcohol on the water in it with a very little powder. Unless the powder rushes out to the edge, the dish is too dirty to do well.)





b. Repeat with fresh water, again very lightly dusting the surface with lycopodium powder. Bring a red-hot iron wire very near the surface. It will be seen that the powdered surface rushes away from that region. (The wire is heated in a Bunsen flame. It must be thick enough to remain very hot when carried to the dish, but not so thick that the heating takes too long. A wire of 18 gauge or 1.6 mm diameter will do well.)

c. Repeat with a new lot of clean water and lycopodium powder using a very small quantity of olive oil – a matchstick dipped in oil and wiped clean should provide enough. Again the lycopodium powder is pushed aside by the film, but this time it remains and the powder does not return as it did with the drop of alcohol.

d. With a fresh, clean dish try placing crumbs of camphor on a clean water surface. If the camphor seems lazy in its movement, it is a sure sign that the surface is oily. A full re-cleaning is necessary. Then a drop of alcohol may be used as a test.

e. With a very clean dish, a pupil will find it interesting to dip a clean finger in a dusted surface and see the 'grease ring' that forms.

NOTES

1. When washing a dish after cleaning it is best to fill it to overflowing. Then hold it with the fingers outside, well away from the rim, and tip it sharply to pour out half the water in it. This may help to carry away residual oil. Remember that a monomolecular film of oil will ruin these experiments. That means that 0.000 01 g of oil can spoil a small dish.
2. If the heating and camphor experiments seem unsuccessful, the cause is probably residual oil. The teacher can test against this by administering a drop of alcohol to a powdered surface when the pupil has cleaned and refilled his dish and is ready to repeat the experiment.
3. In storing apparatus, it is essential to keep the lycopodium far away from any oil or camphor.

Illustration of oil spreading As an illustration of a liquid spreading out until it is one molecule thick (like oil on water) some teachers like to show a demonstration of a handful of sand or lead shot poured on the tray, spreading to a sheet one grain thick. This is a clever illustration, but a misleading one. Pupils take it too literally and think that oil molecules are round. If they were round, the film of oil would be one molecule-*diameter* high. And then, assuming that, it would not only give a misleading picture, but also a wrong picture. Worse still, it suggests that the oil film measurement can tell us the volume of a single molecule, or the number of molecules in a known volume, and thence the Avogadro number when in fact it can only tell us the length of the oil molecule, so that we need further information before we can find its volume.

A much better model can be made by pouring a large number of small pieces of drinking straw into a bowl of water. Cut drinking straws into lengths 2–3 cm long; load and seal one end with a small pellet of plasticine or possibly a lead shot; then close the other end by squeezing. Throw a handful of these into a bowl of water. They will float upright and will even tend to collect together in a flock. This is such a close model that it will repay the trouble of manufacturing the loaded straws.

Discussion of surface tension experiments We speak of the rise in temperature '*weakening the surface skin*, so that the stronger cold skin farther out can pull the powder away'. And we use the same description when we see a drop of oil placed on the powdered surface and spreading quickly.

Yet, the real effect of the added material is much more like a surface *pressure*, pushing out in all directions along the surface; so the earlier experiments with drops and pools of liquid are only a help in drawing attention to surface effects in general.

Cleanliness If the dish is at all dirty, with a little oil on the water surface before we start, the alcohol has much less effect. (*We* know – but we can hardly anticipate the whole business and tell children that a monomolecular layer of oil will suffice to spoil the whole experiment. That means that 0.025 mg of oil will ruin a surface 15 cm square. A finger that has touched the hair of one's head and taken nothing more than its natural oil can spoil a dish after the most careful washing.)

A drop of alcohol forms a good test of cleanness of a dish and its water and the surface is no worse for the test. The teacher can bring an alcohol dropper round to test dish after dish. However, when it comes to allowing a measured drop of oil to spread on a big tray, meticulous cleaning makes too serious a demand; so we must follow Langmuir's method which is described below.

Discussion of the main oil film experiment We use *olive oil* which is a common substance and, as a vegetable oil, has a long molecule with one end that attaches to water and the other end that is inert. (Actually, the chief constituent has a three-fingered structure but the statements we make here are essentially correct.) We tell the children they are going to make a tiny drop of oil (half a millimetre across) and let it spread to a flat patch on clean water in a large tea tray. We then tell them the story of Rayleigh's work and of the assumption, or guess, that he made – that the oil spreads until it is a sheet one molecule thick. We try to make that assumption seem reasonable.

Then when the experiment is done we simplify the arithmetic by taking the little round drop of oil as a cube and the patch to which it spreads as a square. That will yield a smaller estimate of molecule size, two-thirds of the proper result – but never mind, simplicity is best here. The usual instructions to use a *solution* of oil (or fatty acid) and let the solvent evaporate will lead to much too complicated arithmetic. It is *not* suitable here.

This oil film experiment to measure a molecule length is one the children can do if we explain what it is aiming at and then give them plenty of time. The object of the experiment is to have children experience the delight of success in a real atomic measurement. We should give them encouragement, we should simplify the experiment and its calculation, but we should not do the experiment for them. Of course the teacher can do it much more quickly, and that would save a great deal of equipment, but then we should be cheating children of a personal experience of doing science, which will be of enormous value now and later.

As regards cost: this is well worth while even if it makes us economize on some more advanced apparatus. As regards time: we shall gain time in the end if children do their own experimenting now, because it will give them tremendous confidence in atomic knowledge.

All that the children need to know for our important oil film measuring is that the oil *does* spread, and that it goes on spreading until it makes a very thin film which does not seem to want to spread any more. We need to borrow from our chemical colleagues the assurance that oil molecules (of this kind) have one end that is attracted strongly to water and the other end that does not care for water at all, 'a waxy end'; and that these molecules attract laterally so they cling side by side. One might say:

Suppose we poured a whole school of children out on to a muddy playground in a pile. Each child has a good pair of rubber boots on that are safe in mud, but wants to keep the rest of his or her clothes clean. So there is one end of the child that likes mud, the boots, just like the oil molecule's end that likes water. Which way will the children end up, lying down, standing on their feet or standing on their head? What will the whole lot look like if we go on pouring out children till the playground is full? . . . Rather like an army all upright and crowded close together; or like the hairs of a velvet carpet.

Pupils' preparation for main experiment The main experiment with the tray needs two pieces of preparation:

1. Children must see what happens when oil is put on clean water preferably in a small glass dish, with dusted surface.
2. We must tell the story of Rayleigh making an estimate of molecular size, so that the children know what they are going to do with the tray and why they are doing it.

Lord Rayleigh made a guess, one of the earliest good ones, by doing an experiment just like yours in which you put a little oil on clean water and watched it spread. He bought a big washtub 75 cm across, cleaned it carefully, filled it with water, and then put a tiny drop of olive oil on the water. He tried that again and again until he found the amount of oil that would just cover the whole surface of the water in the washtub.

He could test whether the oil had covered the surface by something that you have seen: he put some crumbs of camphor on it. Where there was oily surface the camphor crumbs stayed dead, but where there was clean water surface they rushed about. When he put too much on, the whole surface was covered with oil. He tried again and again till he found just the right amount to cover the whole surface.

Lord Rayleigh knew that oil molecules are long molecules – a whole chain of atoms – and that they have one end that clings to water very strongly. The other end does not mind about water and so it is left standing up from the water. Then the oil molecules will be upright like the hairs of the pile of a velvet carpet.

He expected the oil to spread on water until it wanted to spread no more. How thick do you think the oil patch will then be? Suppose it has spread and spread until it doesn't want to spread any more over the water surface. How thick?

First persuade the children to make Rayleigh's guess, and then emphasize the fact that it was a risky guess, a guess that has now been verified by alternative measurements. Then we are ready for the main experiment.

56 Class Experiment
Measurement of an oil molecule

APPARATUS *item no.*

The oil film kit (item 7) includes 8 sets of the following:

1 Special tray *7C*
1 Rubber bung for drain hole *7D*
4 Rubber wedges for tray *7L*
2 Metal booms *7J*
1 Lycopodium powder dispenser *7M*
1 Cheese-cloth cover *7N*
1 Rubber band for above *7P*
1 Large sponge *7Q*

It also includes 32 sets of the following so that each pupil can have his own:

1 Special holder *7G*
1 $\frac{1}{2}$ mm graticule *7E*
2 Mounted wire loops *7F*
1 10-cm^3 glass beaker *7K*

It also includes:

1 250-cm^3 bottle of pure olive oil *7H*
1 100-g bottle of lycopodium powder *7I*
1 5-cm soft paint brush *7R*
1 Can *7T*
1 500-g packet of vegetable black *7B*
3 kg white paraffin wax *7S*
1 25-g bottle of camphor *7U*

In addition to the above, each pupil will need:

1 Retort stand *503–504*
1 Boss *505*
1 Hand lens *24*

Each group of four will also need:

1 Metre rule *501*
1 Bucket *533*

PREPARATION

The trays should have a layer of molten paraffin wax painted on the bottom, the sides and – especially carefully – the top rim. The booms also should be coated with wax. This should be done at least a day prior to use.

Melt paraffin wax in the can provided in the kit (item 7T). Add a little of the vegetable black (item 7B). When the liquid is hot – almost but not quite smoking – paint it on to the tray with the soft 5-cm paint brush (item 7R).

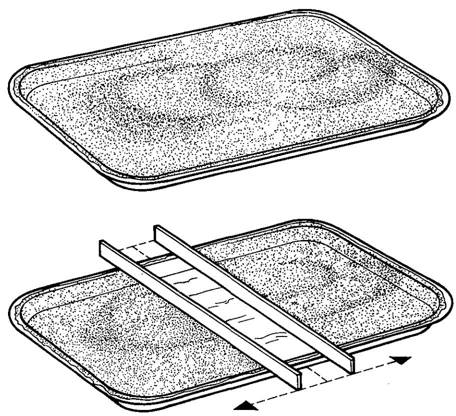
Any thick blobs of wax which form on the rim can be dispersed by repainting with a brushful of very hot, molten wax. (It is *not* advisable to use a Bunsen flame, though that is tempting. A flame playing on the wax surface may add grease, a flame under the tray will melt the unwanted blobs but may also do unexpected damage.)

If any difficulty in waxing the tray is experienced, it is almost certainly due to not having the wax hot enough.

PROCEDURE

Setting up the trays

The prepared tray is placed on the bench with the corner with the drain hole hanging over the bench edge. The hole is closed with the rubber bung (item 7D) from below. The tray is then partially filled with clean tap-water and levelled by careful use of the rubber wedges (item 7L). The tray is then filled to over-brimming with further levelling. The water surface is finally cleaned by slowly moving the two metal booms (item 7J) – also waxed, as described above – from the middle to the two ends of the tray. The booms should be left near the ends of the tray.

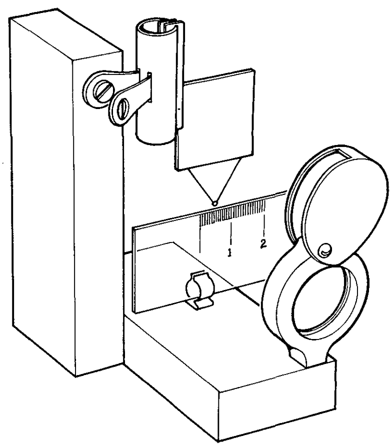


The advantage of this arrangement is that it makes it very easy to prepare the water surface after one oil film experiment ready for the next. It is merely necessary to take up the waxed booms, move them to the centre and sweep the surface as described above.

Preparing the oil drop

It is important that each pupil should do his own experiment. Whereas the trays are shared in groups of four, each pupil should prepare his own small drop of olive oil. Because of the ease with which the water surface can be cleaned, he will also be able to do his own oil film experiment on the water surface.

Each pupil has a loop of very fine wire (item 7F) – steel wire, diameter 0.075 mm, looped and mounted on card – which he dips in his small beaker (item 7K), containing olive oil, to catch a small drop. He suspends the loop in the special holder, fixes the holder rigidly to his own retort stand using a boss. The holder should be level with the eye.



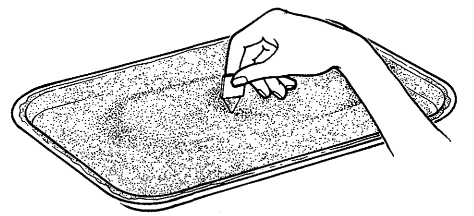
Also fixed in the special holder is a hand lens (item 24) and the $\frac{1}{2}$mm graticule (item 7E). The position of the loop should be adjusted so that the drop is clearly seen against the $\frac{1}{2}$mm graticule when viewed through the hand lens.

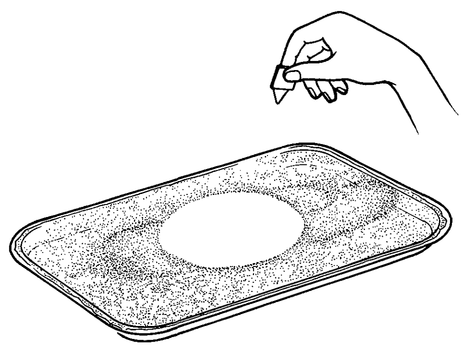
With a second loop of wire, also dipped in oil, the pupil 'teases' the original drop or runs several drops together until it is $\frac{1}{2}$mm in diameter. The special holder enables the pupil to have his hands free. Without some sort of holder – at eye level – his task is much harder. Whatever holder is used it must hold the loop, the graticule, and the hand lens so that the pupil's hands are free and it must be at eye level so that he does not have to strain his neck.

If there is an excess of oil on the loop, the pupil can wipe this off with filter paper.

Doing the experiment

Having cleaned the water surface by moving the waxed booms across it, the pupil lightly dusts the surface with lycopodium powder. When he has adjusted his drop of oil to $\frac{1}{2}$mm diameter, he brings it to the tray and dips the loop with the drop into the water. The metre rule is used to measure the maximum diameter of the patch produced.





(With some water supplies, the patch contracts to a smaller size soon after it is formed. This is probably due to water-softening agents attacking the oil, though this is not certain. Whatever the cause of such a contraction, we believe the proper measurement to take is the initial maximum diameter.)

NOTES

1. To empty the tray, put a bucket underneath the hole and release the bung. Then wash the tray carefully in a detergent solution, such as Dreft, and flush for a considerable time before storing.
2. Since effective waxing of the edges of the tray is essential, it is advisable to store the trays very carefully using, for example, corrugated card to separate tray from tray.
3. Bottles of lycopodium should be stored entirely separately from the olive oil stock.
4. It is important in this experiment to use *pure* olive oil.
5. Teachers will find it well worth while to practise the whole business privately beforehand, so that they know the symptoms of trouble and can help children to get the right size of drop, and can advise when a tray of water is obviously not clean.

6. The teacher will be called in to give advice on the size of the drop; and he should not give any, except to an experimenter who is very discouraged. When he has seen many drops spread, he will know the look of a drop that will 'give the right answer'. He should then be very careful never to judge drops for pupils by using that knowledge.

Calculation of oil molecule estimate The measurements are obviously rough but worth having. The arithmetic to estimate the molecule length will be difficult enough to spoil the game, by dragging in $(\frac{4}{3})\pi r^3$, unless we provide a simplifying trick.

Therefore, teachers should suggest that children treat the oil drop as a cube, of width equal to the diameter of the sphere, half a millimetre here. And they should treat the oil patch as a square instead of a circle – a square of width equal to the diameter of the circle. That will yield a smaller estimate of molecule height, two-thirds of the proper result; but never mind, simplicity is best here.

Remember that, like Lord Rayleigh, you and I are desperate to know something about the size of a molecule because from that we could even make a guess how big atoms are. Any rough measurements would be a tremendous scientific achievement for us. This is a tremendously important measurement that you will remember all your lives. If you want to, you can even take the apparatus home and show the experiment to people at home.

Then each should work out his own result, and post it on the blackboard.

The result of careful measurements is about 1.5×10^{-9} m; and children's measurements will range by a factor as big as three in either direction – yet they will still be within the right order of magnitude.

The result agrees with alternative methods When the children have arrived at some estimate of molecule length, we should tell them that there are other ways of making that estimate (e.g. X-ray reflections from molecule layers in crystals – which they will meet in Nuffield Chemistry. Those agree very well with this estimate, done carefully.)

Proceeding to an estimate of atoms We want to arrive at a guess of the size of a single atom. For that we need the chemical knowledge that an olive oil molecule is about a dozen atoms long. (The simpler fatty acid molecules, which are long chains, range from a dozen to two dozen or more atoms long, adding a standard amount of about 1.3×10^{-10} m or 0.13 nm for each carbon atom added to the chain.) That increment gives us one way of estimating the size of an atom, or at least of a space taken by a carbon atom, provided we are sure that we have added only one more. One might, in theory at least, also make an estimate of the number of atoms in a whole chain by studying the compounds formed when hydrogen atoms in the chain are replaced by, say, chlorine. As a direct test, that could hardly be done; but indirectly, that is what a skilful chemist can do, in organic analysis. We cannot explain all this to children but we might give a simple story like the following:

That is a good guess at the length of an oil molecule. Can we jump from that to a guess at the size of a single atom? Chemists can find out how the atoms are arranged in the big molecule and they tell us its chain is about a dozen atoms long. They can find out how many atoms long each of those molecules is without ever knowing how big a single molecule is or how big an atom is.

In a cold winter you could find out how many children there are in a family without ever seeing the family if the shops will tell you how many pairs of gloves they supplied to that family. Chemists do something rather like that with atoms. They don't fit gloves on to the atoms of the long oil molecule; but they can do something rather like taking gloves off each atom all the way along the chain and putting mittens on instead.

We need not give children that story, or any detailed story. We simply have to assure them that if only we can measure the length of an oil molecule we can borrow some information from chemistry about the number of atoms in the length of the chain to see how big a single atom would be. Suggest dividing by 12, though 10 or 20 would be near enough here.

Data for teachers Atoms range from about 0.1 to 0.4 nm in diameter. Olive oil molecules seem to be about 1.5×10^{-9} m or 1.5 nm long. Fatty acids such as stearic acid range from 2 to 3 nm long, adding 0.13 nm for every carbon atom added in the chain of $-CH_2-$ groups. Since the length from carbon to carbon is about 0.13 nm, we may regard that as a rough diameter for a carbon atom, although the actual chain is a zigzag one.

How many molecules along a postcard? When the estimate of the size of the atom has been made, return to the original question: How many atoms along the length of a postcard? The postcard is about 15 cm long. If we take an oil molecule to be $\frac{15}{10\,000\,000\,000}$ of a metre long that is $\frac{15}{100\,000\,000}$ of a centimetre; so 100 000 000 molecules in line would take 15 cm, one postcard. If our number from the chemists is right – a dozen atoms in the molecule chain – there would be twelve times as many atoms in the postcard length, 12 hundred million atoms.

What does measuring atoms mean? In commenting to children on the size of atoms we should keep in mind the close interaction between the measurements and Nature. The estimates we get here are for molecules or atoms lying side by side or loosely attached to other atoms, or making mild collisions like those between air molecules.

Point out that a tailor can measure the 'diameter' of a man's waist by encircling him with a tape-measure, undoing it and dividing by π, and demonstrate that on a pupil. But a demoniac tailor could use a steel wire like a cheese-cutter and pull tighter and tighter, till he is ready to measure the diameter of his poor victim's spine.

That is true of atoms: with sufficiently violent collisions, one atom moves right in through the electron structure of another; we lose track of the lightweight electrons and see a collision in which there seems to be only a nucleus with a diameter 10 000 times smaller. Nuclear collisions are not restricted to alpha-particles or other charged projectiles. Neutral atoms endowed with the same large energy – which is however much more difficult to give to uncharged particles – will make just the same kind of nuclear collisions.

CHAPTER 8
Energy – a first look
Jobs that need fuel

Forces have cropped up at intervals; and now we go on to forces doing jobs for us, and we begin to mention energy and work informally, with many illustrations, to start acquaintance. With energy – the second main 'concept growing by familiarity' of this first year – we have to proceed carefully. Atoms may be common in public talk, and children may accept our use of them. Energy, however, is a stranger word, likely to bring out misleading prejudices. So we must start with many simple demonstrations, raising a brick, pulling out a spring, twisting, compressing, etc., asking again and again, 'Could you do that without using your muscles and needing food; could an electric motor do that if it is not connected to the mains?' We build up the idea of fuel being needed to do these jobs of work for us. We measure 'work' simply and count the cost of that measurement. We give a strong impression that one cannot get a job done without fuel.

Our survey of forms of energy runs on into 'nuclear energy'. We show a cloud chamber, preparing for it by simple experiments in cloud-making; then we offer diffusion cloud chambers for a class experiment. At the end of this first year we show another way of 'seeing' the projectiles from radioactive nuclei: a simple counter that counts alpha-particles by visible sparks. These are things for a first look at radioactive atoms, with little or no explanation. We leave them, with a promise to return.

ENERGY AND ENERGY CHANGES

In this first year, children should take a first informal look at 'energy' – or, rather, 'energy changes' since those are usually the most important aspects of energy for us. This should be a *very brief* look *to be renewed and discussed in Year 2.* At this point, teachers should consider the time available and plan if possible to get to the end of this year's suggested programme, including without fail the spark counter and both forms of cloud chamber, even if those are at the expense of making the introduction to energy and its forms very hasty and superficial.

Unlike other sections of this course, where we hope that what is done will be done thoroughly so that children gain a good sense of understanding, this introduction to energy is only the beginning of a serial treatment that we shall take up each year for the next four years. This is intended to be literally an introduction, to meet the word 'energy' and shake hands. Acquaintance will come next year, and knowledge and understanding in later years still. Even if we spend considerable time on this introduction, we must not expect children to emerge at the end of this year ready to give clear definitions or carry out successful calculations or even describe energy changes competently.

To change the metaphor, we shall have taken our pupils to look at a strange country in the intellectual world; viewing it from one hill after another, each time seeing quite a different landscape, each time not knowing what to look for; knowing that the trip is important, yet not knowing quite why. Such a trip could be a pleasure and leave useful memories, or it could be a painful rush, spoiled by demands that are too heavy.

By the end of this year we do not expect pupils to understand energy or even to be able to describe energy changes in the right words; but we do hope that they will have seen and learnt some interesting experiments concerned with energy changes, which will prepare the ground for fuller discussion in Year 2. Teachers would be wise to look at the suggestions for teaching energy in Year 2 and its important continuation in Year 4 before embarking on the present introduction.

We must be careful not to build up for energy a reputation as a magic word that will answer any question about why things happen. Yet children know a lot about food and what it does for them and are interested in climbing hills, hauling up loads, shoving things along; and in engines and what they will do. We can make an informal approach to energy by linking children's natural knowledge of food and fuels with their interest in those activities. Children recognize those jobs for which fuel is needed in one form or another; so this is a good point with which to start.

Food We start by asking, 'What does your food enable you to do, besides keeping warm and breathing and generally living?' We encourage as many answers as possible, and ask again and again, 'Do you have to have food for that?' and sometimes we ask, 'Could an engine that uses petrol do that for you instead; or an electric motor that draws on the electric supply?'

57 Class Experiment

Jobs that need fuel

APPARATUS *item no.*
Balloons *57C*
Steel springs *2A*
Bricks or wooden blocks
Pulleys on clamps *40*
Cord *10A*

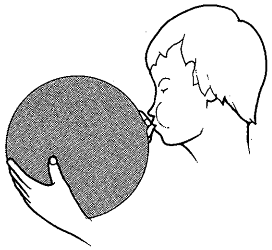
PROCEDURE

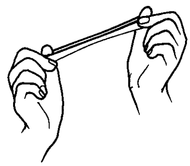
We ask children to do certain things, and to say for each whether they think it makes demands on their food.

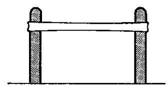
If you had to do that again and again all day, do you think you'd be more hungry? Do you think you'd need extra food if you had to keep it up week after week?

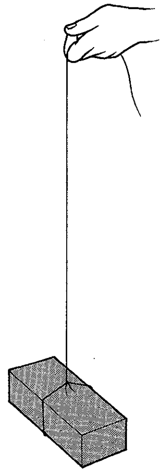
Ask children to:
a. Blow up a balloon: tie off the neck.
b. Put the blown-up balloon on the table and sit and watch it.
c. Hold a steel spiral spring or rubber band between their fingers and stretch the spring by pulling its ends further apart; let go.
d. Repeat this, but instead of letting go, slip the spring over two pegs to keep it stretched.
e. Tie a string to a brick and raise the brick from the floor to the table by pulling the string. Place the brick on the table. Attach a pulley wheel to the edge of the table and run the string from the brick on the floor up to the pulley, over it, and along the top of the table horizontally. Raise the brick by pulling on the string and just hold it 75 cm above the floor.

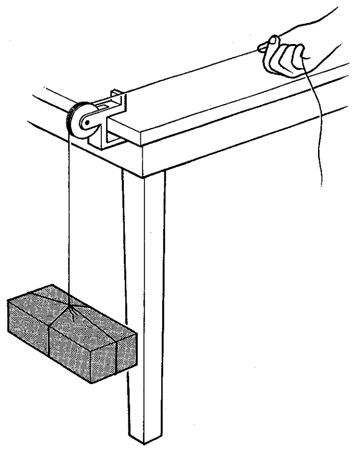
We may then ask the children to do some jobs in their imagination:
g. Bicycle uphill.
h. Turn the handle of a sewing-machine.
i. Climb a mountain.
j. Stir, and go on stirring, a large, thick pudding.
k. Switch on a torch lamp and leave it switched on.
l. Sweep the floor.
m. Light a burner under a model steam engine and let it run.

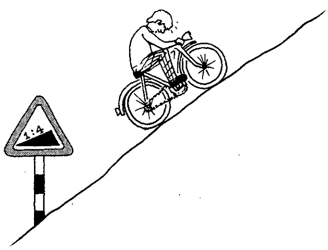


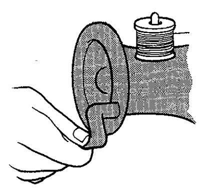


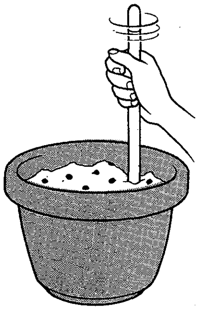


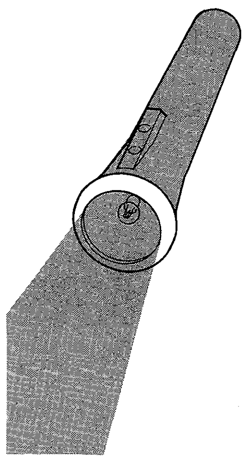


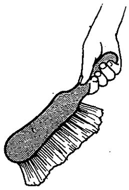


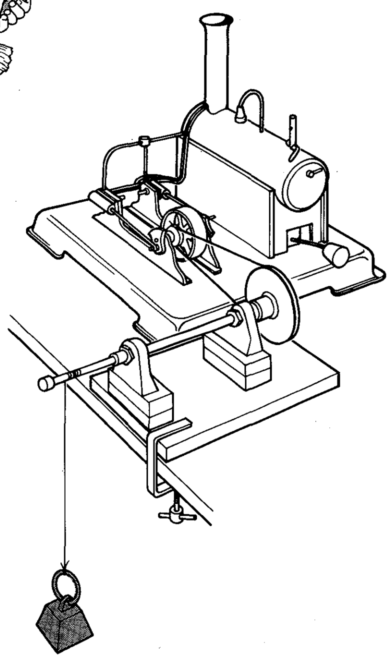












We try to distinguish in the discussion between jobs that *essentially continue to use fuel* or make demands on our food supply, from those which, perhaps after some initial demand, do not involve further energy transfers.‡

The name 'energy' Then we begin to use the name 'energy' saying:

Your food provides some heat to keep you warm, but it also provides something stored up in chemicals in your muscles that makes you able to raise loads, shove things along a rough floor, and do various jobs like that. We say you have got *energy* stored up in your muscles, 'chemical energy' as we call it.

What else has a store of energy like that in it?... Yes, petrol, coal... any others?

We try to elicit suggestions such as fireworks, waterfalls, oats for horses, the electric supply mains.

If someone mentions sunshine, we say, 'Ah... we shall come back to that.' We do not try, just yet, to trace our fuel energy back to sunshine or any other 'original source'. Though that would give interesting stories it would involve us in too many assumptions or assertions in a hurry. We want first to make children form some idea of the jobs that energy transfers provide for; to give them some idea of the forms of energy involved, with common names for them; and a general feeling – given by taking conservation for granted, without discussion at this early stage – that energy is something that shifts from form to form without getting made or lost.

58 Class Experiment
Human energy chart

Stores of energy – food energy

We have introduced energy with the idea that fuels contain stores of energy that can be transferred usefully. And we have included food among fuels. From now on, we might post up a chart of the energy intake in daily food of a man, a woman, and a child; and then some measured rates of drawing on food energy for various activities. The energy units in such a chart, kilojoules, will raise questions, but we may be wise to postpone discussion and simply say the numbers give comparative amounts and rates. (This chart is also given in the *Pupils' text*.)

‡ In the course of this discussion, some pupils will raise questions about 'getting tired when just holding a load, or when carrying a load along on level ground'. We do draw on food energy in doing something like that and we may even feel more tired than the actual energy transfer would justify. For a discussion of this difficult question, see the Note in the *General Introduction*, p.32. In early discussions we should avoid spending long on these particular jobs, and just point out that a load can be held high up by a shelf, which would not need food; and a load can be transported along the level on almost frictionless rollers, without needing much energy.

HUMAN ENERGY CHART

Energy from food

Here is a table showing the energy which 100 grams of various foods can produce. The energy unit used is called the kilojoule.

Food			
Sugar	1660	Milk	280
White bread	1010	Butter	3350
Oatmeal	1700	Cheese	1800
Cornflakes	1550	Margarine	3350
Potato (chips)	1010	Egg (fried)	1010
Baked beans	390	Beef (roast)	1050
Cabbage	100	Fish cakes	920
Orange	150	Ice cream	840
Apple	190	Buns	1290
Rhubarb	20	Plain chocolate	2300

Human energy demands

How much energy do we need to take from food each 24 hours? The answer depends very much on the sort of people we are, particularly our age and job. Some average figures for overall use of energy are shown in the following lists.

Boys and Girls	
0– 1 year	4 200 kilojoules per day
2– 6 years	6 300 kilojoules per day
7–10 years	8 400 kilojoules per day

Teenagers	*Boys*	*Girls*
11–14 years	11 500 kilojoules per day	11 500 kilojoules per day
15–19 years	14 700 kilojoules per day	10 500 kilojoules per day

Adults (20 years and over)	*Men*	*Women*
Lying in bed	7 400 kilojoules per day	6 300 kilojoules per day
Light work	11 600 kilojoules per day	9 500 kilojoules per day
Heavy work	14 700 kilojoules per day	12 500 kilojoules per day
Very heavy work	21 000 kilojoules per day	

Pregnancy	
Early months	10 000 kilojoules per day
Later months	11 500 kilojoules per day
Nursing the baby	12 500 kilojoules per day

Energy needed by a young man to perform some useful jobs	
Resting in bed	4 kilojoules per minute
Standing still	8 kilojoules per minute
Walking at 5 km per hour (3 m.p.h.)	15 kilojoules per minute
Digging a ditch	28 kilojoules per minute
Running fast	42 kilojoules per minute

Generally speaking, energy use by an adult man ranges from 53 kilojoules per minute for the heaviest work to 11 kilojoules per minute for the lightest. Such estimates are, of course, only averages. Just as our muscle strength varies from one person to another, so do our energy needs for the same rate of doing a mechanical job.

Useful jobs need energy transfer The teacher should point out that in all those changes where something has to be provided for a 'useful job', like lifting up a load to the top of a building, there is something that seems to shift from one kind to another. Something that was in our muscles that shifts to something in a stretched spring or a raised load or a lighted lamp. We call that something 'energy', saying, 'Energy is something which we get from stored-up form in fuels, which, in moving across to some other form, does useful jobs for us.'

We make a joke, saying, 'If you want to know what a "useful job" is in this description of energy, I can tell you: it is one of those jobs which needs some energy supplied from some fuel!' This circular description is not as stupid as it sounds, because in dealing with it we can build up considerable familiarity with energy and with 'useful jobs'. We shall suggest that in shifting from one form to another, energy is never lost but keeps the same total, like money that circulates in a town.

Names for forms of energy

In this discussion it is helpful to use some simple names for the forms of energy involved. Among them are:

Springs energy (= strain energy) We point to a stretched spring and say that the spring also has 'something like the energy that fuel holds stored', because, instead of using fuel to drive an engine or using food to keep a man going, we could use a stretched spring to pull on a string and haul a load up or do some other useful job. So a stretched spring or a wound-up clock spring has a store of 'springs energy'.

Chemical energy In using food to do a useful job, a mans shifts energy from the store of chemical energy in his muscles to some other form, 'springs energy' perhaps.

Uphill energy A simple, graphic alternative for gravitational potential energy.

Motion energy A simple alternative for kinetic energy.

Light energy We use this term for radiation energy or any other name for the energy of electromagnetic radiation. At this early stage, the word 'radiation' will not make things clear to our pupils – particularly since our class experiments on radiation are yet to come – and we should be teaching in a mistaken order if we started referring to waves at this stage. It is of course unfortunate to restrict our naming by using a word that usually refers to the visible spectrum alone. We must at once explain to pupils that we are thinking of light itself – all the colours, red, orange, etc. – *and* some 'invisible light' which our eyes do not notice, such as ultraviolet light and some other kinds beyond the red. After pupils have done the class experiments of the 'radiation circus' we might wisely change to 'radiation energy'. At the moment, however, we want to keep the naming simple when we are trying to deal with this important and difficult concept.

We speak briefly of *heat*, without defining it or measuring it, yet suggest that it plays an important part in the energy story; because, as we know, heat can drive an engine to haul up a load for us or do other useful jobs.

This suggestion should be very brief and light. It would be better to omit it altogether than to expand it into statements that would upset later teaching. Teachers are advised to look at the treatment suggested for heat and mechanical energy in Year 4.

The child's language and technical words It is true that children beginning science like to learn long names – they feel they are making advances into a new technical region of the adult vocabulary. There is no harm in that, as long as learning long names does not become an end in itself, or a substitute for understanding science. Names of technical instruments, or full names of plants or animals, are harmless and grand. But here where we are embarking on difficult new ideas, we shall gain greatly by using very simple names, temporarily.

At first glance, teachers may feel that such names are too informal, undignified, not likely to be acceptable to children. But experience shows they are a great aid towards our goal of understanding.

Two forms of energy with which the teaching of energy is often started – potential energy and kinetic energy – need very careful introduction: to children they are not familiar or obvious like heat or the energy stored in a spring. The terms 'uphill energy' and 'motion energy' are unlikely to spoil the beginning of that understanding with young pupils.

59 Class Experiment
The energy circus

APPARATUS *item no.*

1 Malvern energy conversions kit *9*
including:
1 Motor/generator unit *9A*
1 Switch unit *9C*
1 Lamp unit *9D*
1 Line shaft unit *9F*
1 Steam engine unit *9I*
1 L.T. variable voltage supply *59*
2 G-clamps (small) *44/2*
1 500-g mass
1 1-kg mass *32*
5 Lengths railway track *10R*
2 Flat trucks *10S*
2 Horseshoe magnets *50/2*
2 Wooden blocks with buffers *10T*

PROCEDURE

The teacher should show, or he might arrange for the children to show in circus form, a number of experiments that illustrate or involve changes of energy. Such experiments are more for the fun of seeing the changes and hearing talk about energy – details for discussion of the changes can wait until Year 2 when more changes may be shown. In the *Pupils' Text* six such experiments are suggested:
a. A battery lighting a lamp. An example of chemical energy being transformed to 'electrical energy' and then to heat and light energy.
b. A heater running a model steam engine. A model steam engine is included in the Malvern energy conversions kit (item 9I). The makers' instruction for use and care of the engine should be read and carefully observed. It is particularly important to dry out and oil the machinery if the engine is to be stored from year to year.

The steam engine can be operated using solid fuel or the laboratory gas supply. Methylated spirit burners can also be used, but they are not always as effective. When the steam pressure is up, turn the steam engine by hand until the condensed steam has been expelled. The engine will now run freely.

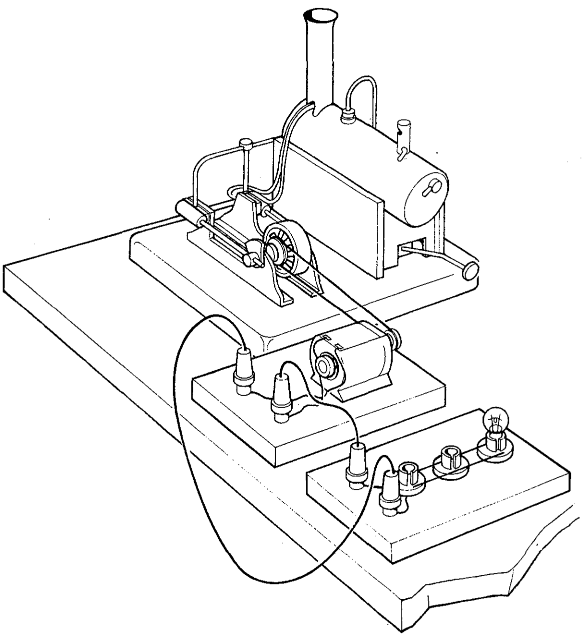
c. The model steam engine lifts a load. The engine should be clamped to the bench with a G-clamp and likewise the line shaft next to it. The small pulley on the engine should drive the large pulley on the line shaft by means of a belt or rubber band.

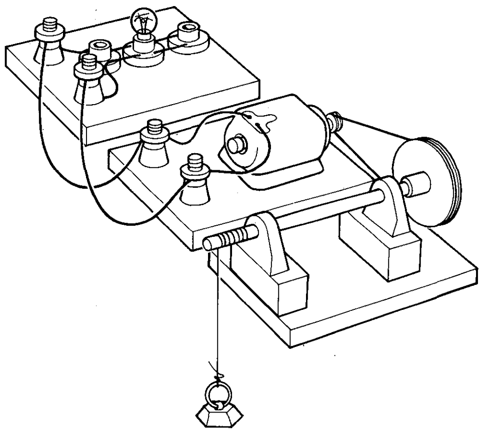
A length of cord should be attached to a mass on the floor (about 500 g is satisfactory) with the other end attached to the line shaft. The engine will raise this load, giving it 'uphill energy' which is drawn from the chemical energy of the fuel.

d. The model steam engine drives a dynamo to light a lamp. The steam engine is used as in *c*, the belt or rubber band now being used to drive the motor/generator unit (item 9A). Both the generator and the steam engine should be firmly fixed to the bench with G-clamps.

The output of the generator unit is connected to the lamp unit (item 9D). It will be noticed that switching on and off the lamp produces a change in the mechanical load on the steam engine.

It is effective to use two or three low-voltage lamps in parallel. With all the lamps alight, the engine labours heavily; with none alight it races. (The lamps may be given a half-turn in their sockets to switch them on or off.)





e. A load falls down and spins a dynamo to light a lamp. The motor/generator unit (item 9A) and the line shaft unit (item 9F) are clamped next to each other. A cord is secured to the axle of the line shaft, the lower end of the cord being attached to the 1-kg load. The line shaft is rotated so that the load is held close to the shaft and about 1 metre above the floor. The generator is connected to the lamp unit (item 9D). The load falls, drives the generator and lights the lamps.

f. A moving cart collides with another moving cart. Fix the horseshoe magnets on the trucks so that the magnets repel each other when the trucks are near together. The magnets can conveniently be fixed to the trucks with Sellotape. Push one truck towards the other so that they collide with the repulsion between the two magnets driving them apart.

Then replace each magnet by the buffer springs, so that when the trucks are pushed together, the springs collide and the trucks rebound as they did with the horseshoe magnets. The buffer springs, mounted on blocks of wood, can be fixed to the trucks with Sellotape or elastic bands.

Describing energy changes As suggested in Section VI of the *General Introduction*, energy changes can conveniently be summarised by stressing the nature of the change using the form, 'When a load falls down, its energy changes FROM uphill energy TO motion energy.' Teachers may wish to use this form, anticipating its extension in Chapter 13, where the measurement of the energy transfer as work is considered. Examples are included as questions in the *Pupils' Text* at this point.

More about uphill energy

60 Demonstration

Jobs a brick can do – if it is high up

APPARATUS *item no.*

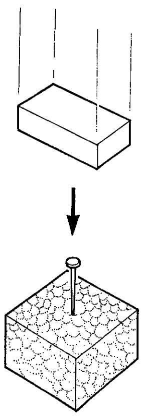
1 Brick *40*
1 Pulley on clamp *40*
1 Large compression spring *88*
1 Motor/generator unit *9A*
1 Line shaft unit *9F*
1 Lamp unit *9D*
3 G-clamps *44/1*
Cord *10DD*
1 Retort stand base *503*
1 Long retort stand rod
1 500-g mass
1 L.T. variable voltage supply *59*

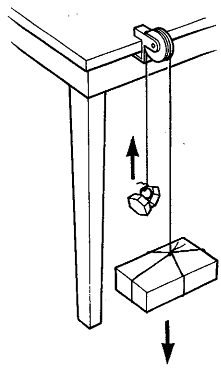
PROCEDURE

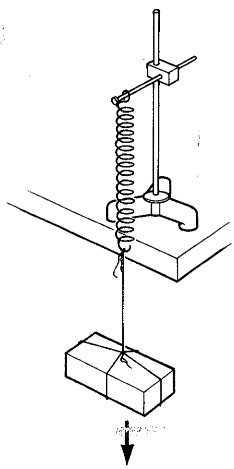
Place a brick on the bench and ask for a description of it. The pupils will probably give many details but no mention of its position. Move the brick to the floor and ask for a description of it. Lead the pupils to realize that the brick higher up can 'do a job for you'. Show examples of such jobs being done, to illustrate this.

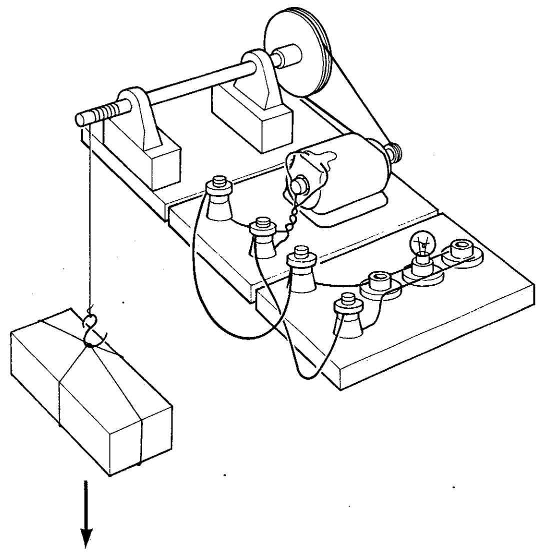
Let the brick:

(*i*) accelerate by falling vertically;
(*ii*) lift another load, by means of a cord and a pulley;
(*iii*) stretch a horizontal or vertical spring;
(*iv*) pull down a cord that is wrapped round the axle of a shaft connected to a dynamo (as in Experiment 59 above).









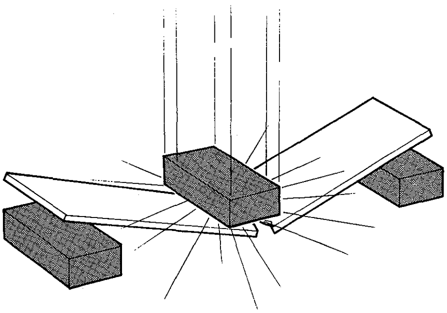
61 Demonstration
Motion energy does a job

APPARATUS *item no.*

3 Bricks
1 Piece of hardboard about 30 × 15 cm

PROCEDURE

The teacher places a brick on a hardboard 'bridge' (across two other bricks) and invites a description. Then he raises the brick about a metre and lets it fall to the floor. He lets it fall on the hardboard and break it. He asks for a description of the brick just before it hits the floor. This leads to the idea of a moving brick being able to do useful jobs as it comes to rest.



NOTE

Where the floor may be damaged by a falling brick, teachers may wish to wrap the brick in newspaper before letting it fall.

Suppose now that we lifted that brick back to the table and then put another of the bricks by its side. Twice as much chemical energy had to be shifted from food energy to get the two bricks up there from the floor as to get one brick up there. How much uphill energy would the three bricks have if placed side by side on that table top?

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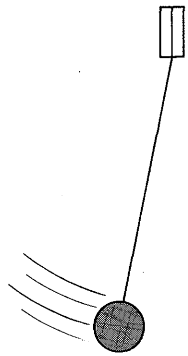
62 Demonstration
Energy and the swinging pendulum

APPARATUS *item no.*

1 Simple pendulum bob *527*
Cord for pendulum *10A*
1 Retort stand, boss, and clamp *503–506*
2 Bits of metal or wood

PROCEDURE

Suspend a simple, massive pendulum bob from a clamp by a cord at least 1 m long. This cord should be firmly clamped at its top end between two bits of metal or wood with their lower edges flush. This clamping device should be supported either from the ceiling or from a rigidly supported retort stand. The more massive the support system the better the demonstration; a light support and a careless assembly for clamping the cord at the top allow the energy in the system to leak away too readily.



Pupils watch this simple pendulum (without any attempt to do any timing, or reference to its isochronous property). We want the children to look at changes of energy, from a store of uphill energy to motion energy and back again. (Some teachers prefer to show a ball rolling in a bowl or on a curved curtain rail.)

The teacher should point out that at the lowest point of the swing the bob is moving fast so it must have considerable motion energy. As it swings to its highest point, that energy decreases and disappears but the bob regains it all by the time it gets back to the lowest point. We imagine some storage system so that the energy of the moving bob is not really lost as the bob climbs upward, but goes into an invisible, stored-up form – uphill energy.

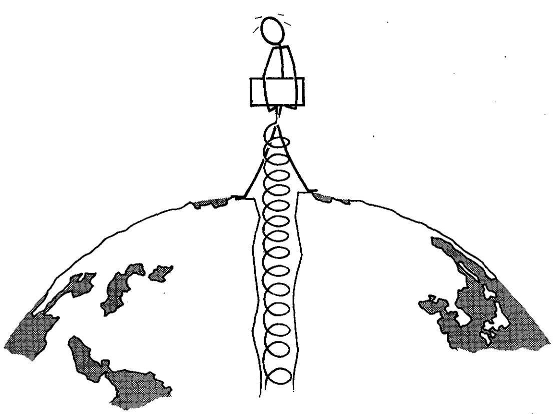
This invisible uphill energy fits our observation that the bob repeatedly regains its full motion energy. It also fits our hope that we can find something in Nature that stays constant. (See the note on the word 'Constant' in the *General Introduction*, p. 46.) In other words, we suggest that the visible changes of motion energy are really only *exchanges*. We should not say, at this stage, that the behaviour of the pendulum *proves* that the total (motion energy + uphill energy) remains constant. We should rather put this as an idea that the pendulum illustrates.

Then the question will arise, 'What happens to the energy when the pendulum's swing grows smaller and smaller?' We should ask for suggestions about that. It would be wise not to give any answer now, but to leave that question as an interesting one for a later year.

If we offer a pendulum for a class experiment it should be used only as something to watch while it makes energy changes. To start timing the pendulums at this stage will lead to an interested, obedient, careful class with their thoughts narrowed down to getting the right measurements when we are trying to explore a very important concept.

The imaginary spring: feeling for gravitational potential ('uphill') energy

In discussing examples where potential energy is involved, questions about what it really is, and where it really resides, may arise. We can help pupils to think of uphill energy stored up in the gravitational field that connects the Earth with the raised load if we tell them an artificial story:‡



Imagine a spring connected between the load you raise and the centre of the Earth. There is no real spring but the pull of that stretched spring is just an imaginary idea to help you think about the way the Earth pulls on the load.

If the spring is *very long* as it is in this case, reaching all the way from the centre of the Earth to you, you will not stretch it much when you pull the load up a few centimetres. You will not change its length much; only from 6400 km to 6400 km plus 20 cm. So you will not change its pull very much however tightly stretched it already is. Even if there were a real spring you would not expect to feel its pull growing stronger when you raised the load higher. And in the case of the pull of the Earth, gravity, we do not notice any increase when we raise something higher up. Actually there is probably a very slight decrease but far too small to feel. So if you like to try this experiment of imagining you need not worry about the spring getting any stronger as you stretch it a little.

Try the following experiment yourself: Stand with your feet apart, hold a brick in your hands and feel how heavy the brick is. Feel its weight. Feel how the Earth pulls it down. If you don't believe the Earth pulls it down, let go and see what the Earth does to the brick.

Pretend to yourself that the pull of the Earth, which you can feel, is the pull of a long stretched spring that is attached to your brick and runs down through a hole in the ground to the centre of the Earth. You will find it difficult to imagine that spring if you keep your eyes open and can see that there is no spring there. So now shut your eyes and think about that spring and raise the brick up, holding it with your two hands. As you haul the brick up, you can feel that spring s-t-r-e-t-c-h-i-n-g. Keep your eyes shut, lower the brick, and let the spring contract a little. Now pull the brick up and stretch the spring. Did some of you manage to imagine the spring?

If children visualize this long spring being stretched, some will bring in their knowledge of springs and expect gravity to increase with height above the Earth – the 'spring' growing stronger as it stretches. If so, the teacher needs to explain again that this imaginary spring, all the way to the centre of the Earth, is so long that any ordinary stretches would not make it change its strength. Then, to avoid the story being misleading, he should add a warning that the real gravitational 'spring pull' of the Earth gets weaker as one goes farther out. But this is not the moment to go into any inverse-square story.

(Teachers will find this an amusing experiment to try with adults, with whom it succeeds more easily than with children. This idea of a spring will be useful in thinking about gravitational field strength; but we certainly must not allow that spring to become too real.)

ATOMIC ENERGY

(This short section on atomic energy should not be postponed to a later year.)

We can say, since everyone has heard of it already, that atoms have energy stored up inside them; and only very rarely can we get at any of that store of energy and release it or use it. A few common

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‡ Some teachers find this experiment in imagination and suggestion easy and profitable; others find it of little use. It depends on the general feeling of the class and the extent to which the teacher can call upon their imagination. We should, privately, remember that the most intelligent people are often the most suggestible.

kinds of atom, the heavy radioactive ones, do not stay the same for ever, like common copper or sulphur, but suddenly unlatch a small part of their store of energy and shoot out a small 'bullet' from the very centre of the atom.

Would you like to see that happening? Of course you will not see it directly because, for all we know now, atoms are much too small to see, but we can show you experiments that show the effects of radioactive atoms blowing up and shooting out bullets.

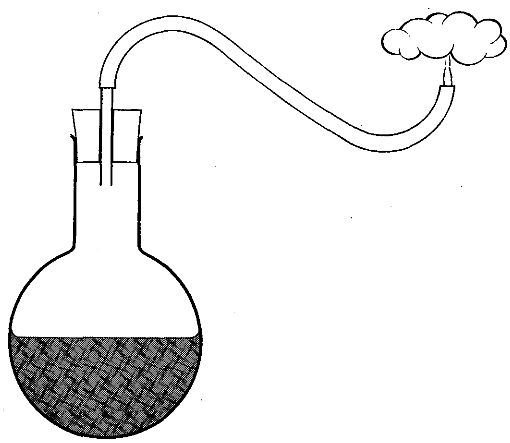
Cloud chamber

If the cloud chamber experiment is to 'make sense' and give the feeling that it really is telling us about radioactive atoms, then we must prepare the ground with ordinary cases of cloud formation. Then we show a cloud chamber. It is new and mysterious: but it is not possible at this stage to talk about ions and about supersaturated vapour and condensation.

63a Demonstration
Making clouds and fog

APPARATUS *item no.*

1 500-cm^3 flask with bung and glass tube *540*
1 Glass tube drawn to a jet (about 2 mm)
1 Bunsen burner *508*
1 Tripod *511*
1 Compact light source *21*
1 L.T. variable voltage supply *59*
1 Retort stand, boss, and clamp *503–506*
1.5 m rubber tubing



PROCEDURE

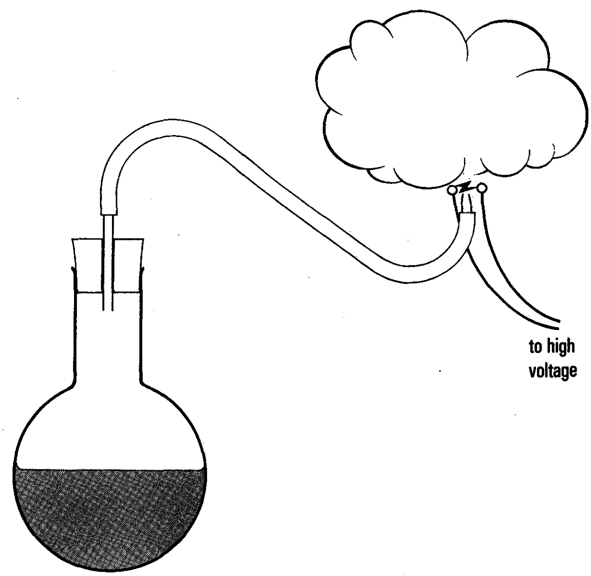
Since the equipment is to be used in a second experiment it is advisable to assemble the equipment so that the jet is separated from the flask and the burner (which is producing ions) by at least a metre. When the water is boiling vigorously attention should be drawn to the jet, the cloud and the gap between them.

To make it clearly visible to the class, project a shadow of the jet and the cloud on the wall or on a screen, using the compact light source at a distance of a metre or so from the jet.

63b Demonstration
The effects of sparks on the steam cloud

APPARATUS *item no.*

As above, together with:
1 Van de Graaff generator *60/1*



PROCEDURE

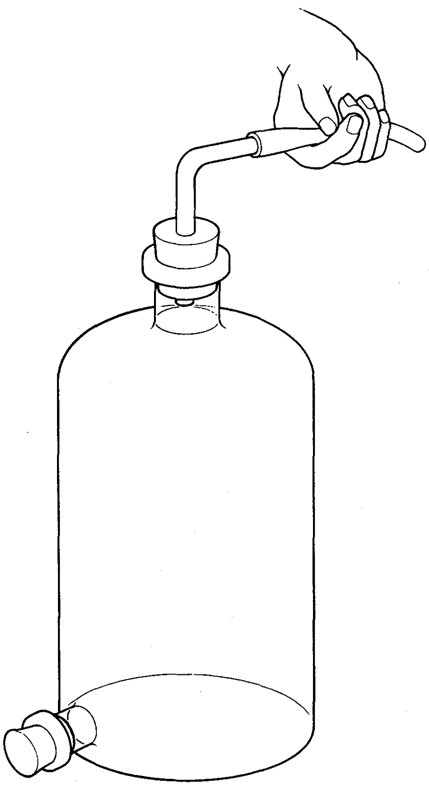
If an electric spark passes through the invisible vapour just outside the jet, before the cloud forms, one can see the effects of ions in promoting a dense cloud a little earlier. The boiling flask must be far away or the Bunsen flame will itself make enough ions to spoil the demonstration. A Van de Graaff generator will make a spark that shows a clear effect. The spark should pass across the mouth of the glass jet from which the steam emerges.

Arrange two wire electrodes to form a spark gap about 5 mm wide and about 3 mm above the glass jet. Switch on the generator so that a stream of small sparks passes through the jet of steam. The cloud will intensify markedly due to the sudden production of ions which act as condensation nuclei.

63c Demonstration
Making fog in a bottle

APPARATUS *item no.*

1 Aspirator (10 litre) or large flask *523*
1 Bung with glass tube and short length of rubber tubing
1 Lamp *46/2*
1 Bung to close the lower outlet of the aspirator



PROCEDURE

1. Put a few cubic centimetres of water in the aspirator. Close with the bung and tubing attached. Blow down the rubber tubing to raise the pressure inside and then pinch the end of the tubing. Allow the air to expand by removing the bung. A cloud will be seen. After the cloud is formed, replace the bung and tube. Blow into the bottle in order to show the cloud disappearing.

For the cloud to be clearly visible by the class, it needs bright lighting from the side and a very dark background, in a partially dark room.

2. If the cloud is allowed to settle and this is repeated several times the air in the aspirator will become relatively dust free and the clouds will be poorer.

Throw a lighted match into the aspirator. Good clouds will again be produced, showing the great effect of providing smoke-dust or ions as centres for cloud drops. (Unless we feel desperate for a familiar 'analogue' we should not refer to the cloud trails made by jet aircraft, because the mechanism is different.)

Expansion cloud chamber

Then children are ready to enjoy seeing alpha-particle tracks. If this is accompanied by a great sense of mystery, that does not matter at this stage, because we should at once explain:

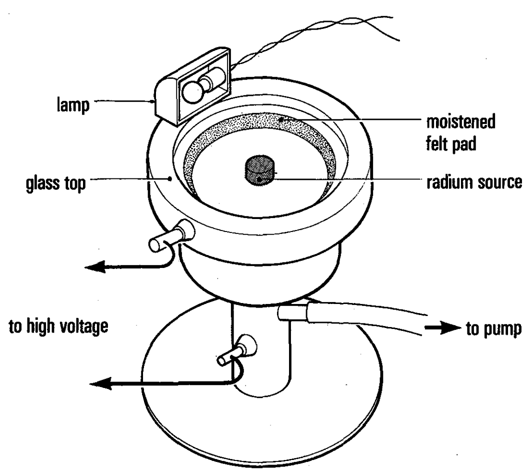
This is only a first look at radioactive events. We shall come back to the cloud chamber and explain it later, when you know a lot more physics, which you will need before you understand the whole story.

Mankind lives by such promises throughout life, from childhood to old age: it is not a silly way of teaching, it does *not* spoil things by skimming the cream: it is the way our knowledge grows. These experiments are new and strange: the interpretation of what one sees is not obvious, and it is not clear to beginners what they should look for. In this case, therefore, it is wise to prepare the ground by showing the children the kind of thing to look for. So before using diffusion cloud chambers for a class experiment, children should see a clear demonstration with a good expansion cloud chamber. That will show tracks clearly and easily at just the expected moment; and children can see the tracks quickly by crowding round in small groups. The long alpha-particle tracks that appear at each expansion are easy to see (and agree with the usual photographs).

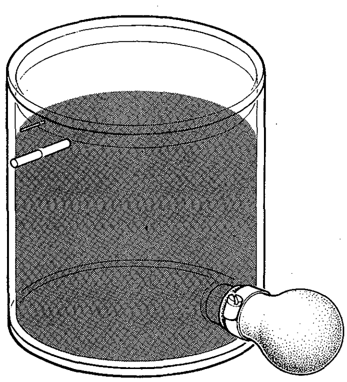
64a Demonstration
Cloud chamber

APPARATUS *item no.*
Expansion cloud chamber *18*

PROCEDURE
Ideally, this chamber should be a projection chamber so that all the children and the teacher are watching the same events. However, bench cloud chambers are more readily available. The setting up and operation of each of the cloud chambers available varies from model to model. The manufacturer's instructions should be followed closely for the best results.



A rubber bulb (like the ones used on battery hydrometers) squeezed by hand and released, will produce the expansion more reliably than a bicycle pump. The volume of wet air should be increased by a piston directly under it, rather than by air flowing out through a tube to a pump – the latter arrangement may produce unwelcome currents, as well as looking less direct.



If the wet air is contained in a cylinder whose bottom drops as a moving piston, pupils are somewhat less likely to make the mistake of thinking that the alpha-particles are pulled out of the source by the pump! For a simple model, the moving piston should be simply a column of water. The rubber bulb is full of water and connected to that column, so that by squeezing it one can raise the column and momentarily compress the air above. The region of wet air is illuminated by an ordinary electric lamp bulb, well shielded.

Before buying a cloud chamber, make sure it is a model that works easily and continues to do so consistently – this is too expensive an instrument to be bought on optimistic hope. In all such cloud chambers, it is important to avoid letting water coat the source, because even a thin film will stop alpha-particles. It is also important to remove the ions that have been formed by alpha-particles a short time before the expansion at which one wishes to see the tracks. Those ions would collect drops of water all over the field and spoil the picture. Therefore an electric field must be applied. In some models, quite a small voltage is needed. In others, it is better to have a plastic lid to the chamber and charge that electrostatically by rubbing – but in that case the field may well fail to reach the proper region.

Teachers may be tempted to save time and cost by omitting the expansion cloud chamber and proceeding at once to the class experiment with diffusion cloud chambers. We urge them very strongly not to make that economy, but to show a good expansion cloud chamber first.

64b Class Experiment
A simpler cloud chamber

After showing the expansion cloud chamber, distribute Taylor-type cloud chambers round the class, one for every four children. Allow them plenty of time to watch the tracks. This is something to be enjoyed and should not be hurried. They will occasionally see strange things in the chamber, which add to the fun of observing. Notice the random appearance of the disintegrations. If possible, do not point this out but offer a hint that will give children a chance to notice it.

APPARATUS *item no.*

8 Taylor cloud chambers *28*
8 Illuminants *47*
1 CO_2 cylinder *19/1*
1 Dry ice attachment *19/2*
8 Transformers *27*

PROCEDURE

To set up the chambers, methylated spirit is put on the padding inside the top of the chamber using a dropper. A drop or two may also be put on the black base of the chamber and allowed to spread over it.

The base of the whole apparatus is unscrewed and a little dry ice from the special carbon dioxide cylinder put in contact with the base plate. The foam is put back to keep the dry ice in contact with the plate and the base cap screwed on again and the chamber inverted.

It is important that the cloud chamber be level: it should be placed on the three wedges provided, which can be adjusted to get it level (if it is not level, convection currents moving in the chamber will be seen and these can be used as guides in levelling).

The top must be put back on the chamber. Rubbing it with a handkerchief will charge it sufficiently to provide an adequate electric field inside the chamber to sweep away old ions. Illumination is important and the illuminants provided should be used and adjusted so that there is a layer of illumination a few millimetres above the base plate. Alpha tracks will be seen coming from the weak radioactive source, inserted in the side of the chamber, usually within 30 seconds of setting it up.

NOTES

1. If the tracks are not sharp, try rubbing the top again to improve the electric field.
2. Surprisingly little dry ice is needed in these chambers. Practice will show the teacher how much is required, usually about 2 or 3 cm^3.
3. To obtain some solid carbon dioxide from the cylinder, fold a piece of closely woven cloth (preferably of dark colour) in the form of a bag. Hold this bag tightly round the nozzle of the cylinder and open the valve at full blast for 5 to 10 seconds. Where the cylinder is of the siphon type it should be kept upright. Other cylinders should be held upside-down during this process.
4. In schools where several classes are following the Nuffield programme, it may not be feasible to manufacture the supply of solid carbon dioxide from the cylinder. It will be necessary to order a block from the suppliers. Such blocks are easily obtainable, delivered by railway. See Appendix to *Teachers' Guide*, Year 4 for details on the availability of solid carbon dioxide in block form for use in schools.
5. It is possible to make the solid 'snow' by expansion before the lesson begins and to store it in a wide-necked Thermos flask.

Descriptive story of radioactive events Explain that we shall learn more about these radioactive substances and that we shall see the vapour trails again later in the course. Resist the temptation to say too much: leave the subject as something to look forward to on its next appearance. We do have to give a little explanation at this point: we should say:

> Something comes out from the radioactive atoms and does a good deal of damage as it flies through the air leaving things there on which water drops can start.

But the time is not ripe for talk of electrons being knocked off atoms and ions formed. We might give the cornfield story, said to be due to Andrade:

> Suppose a cannon ball is fired through a field of ripe wheat. If you were watching from a helicopter up above, the ball would move too fast for you to see it and you would hardly notice the track marked by broken stalks. But wait half an hour and the track would be marked by a line of dark birds settled on the broken stalks.

In a later year we can give the next stage of explanation:

> A radioactive atom suddenly spits out a small piece, from its innermost core. In doing that, its nucleus acts like a gun, hurling that small piece out with vast kinetic energy – at the expense of a fraction of its own store of nuclear energy. That piece is hurled out so fast that as it blunders through the surrounding air it can knock a chip off thousands of air molecules. Those chips are electrons each with a negative charge. An air molecule that has lost one is left with a positive charge; it is a positive 'ion'. And the electron that has been knocked off will soon be collected up by some other air molecule nearby to make a negative 'ion'. So the path of the small particle that is hurled out by the radioactive atom is marked by a mess of + and − ions of air. Little water drops then form on those ions and mark the path. Of course, you never see any sign of the high-speed particle itself – it has flown through before the water drops form on the ions.

Teachers who look at the account above will see time is not yet ripe even for that informal account.

Cloud chamber photographs An adult physicist can glance at a cloud chamber and see the tracks at once; but to a child these are new and strange and need watching. We must give plenty of time; then, after showing a cloud chamber, we should post up large photographs, and leave them up for some time. Some teachers will want to display other pictures as well as the simple sheaf of alpha-particle tracks, for example, pictures that show nuclear collisions, etc., with a fork. Those will promote keen questions and promises of future explanations. Still more complicated pictures, such as bubble-chamber photographs, merely produce confusion at this time – they are 'abstract art' in physics and need much more time and training for a sophisticated understanding of the events they reveal.

Radioactive events with counter

And now, at the end of the first year, we should offer another way of seeing the effects of radioactive events: some form of Geiger counter (not an electroscope being discharged, because, while it is just as mysterious, it fails to show the individual atomic events). We suggest a spark counter for this.

The spark counter shows alpha-particles as individual random events. At this stage we should not explain it but simply say:

This is something which responds to the things which made the tracks in the cloud chambers. By counting the sparks, you can count radioactive atoms blowing up and shooting one alpha-particle each into the space behind the wires. You are counting single atoms.

I cannot explain to you how this works yet. You will have to learn a lot more physics about moving things and electric charges and electric fields and changes of energy before you can understand this. But you will learn how it works; and you will see it again.

65 Demonstration

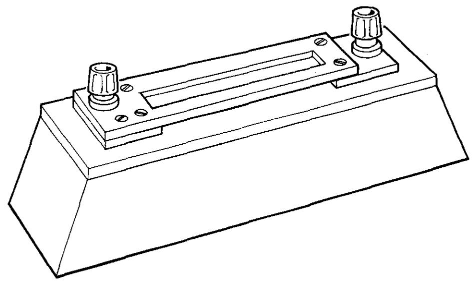
Spark counter

APPARATUS *item no.*

1 Spark counter *17*
1 E.H.T. power supply *14*
1 Radium source *16*

PROCEDURE

The high-voltage lead of the spark counter is plugged into the positive terminal of the E.H.T. supply (without the 50-megohm safety resistor). The other terminal on the counter is connected to the negative terminal of the supply, which in turn is earthed.



The voltage is increased slowly until the counter is just below the point of spontaneous discharge. Usually about 4500 V is necessary. If now the radioactive source is held a centimetre or so from the counter, sparks will be seen and heard. The random nature of the process will be apparent.

NOTES

1. The most effective demonstration occurs with counters in which a grid of parallel wires is mounted just in front of a smooth plate.
2. Any kink or bend in the wire in the counter is liable to cause a spark discharge at that point. If that happens the wire should be replaced.
3. A continuous spark (which will very soon damage the wire) shows the voltage is too high.
4. The counter should be dust free. Dust around the stretched wire can often be blown away.

YEAR 2

CHAPTER 9

About forces

Pulling and pushing; turning and twisting

For many children this chapter will see the commencement of Year 2 of the full course. It begins with a series of experiments which return to the ideas of force that have been implicit in earlier work. The essential points are to see and feel the forces involved in deforming things (stretching, compressing, twisting, bending), to discuss briefly the 'turning effects of forces', and to experience the forces of attraction and repulsion between magnets. With a fast group, the idea that a collision involves repulsions that grow steeply at close approach might begin to modify the natural view that a collision must have a smash of 'contact'.

MORE ABOUT FORCES

This first lesson (which may well spread to two periods) should be a mixture of demonstration and class experiments. Start by asking the children what forces are, and accept all the suggestions which are concerned with forces pushing and pulling and having effects such as stretching, twisting, bending, etc. Point out that the easiest forces to know about are the ones that we feel ourselves when a muscle helps us to pull up a weight or hold a load, or when a pencil makes a dimple in our cheek, or when someone pulls our hair.

Teachers may like to ask some questions about the ways in which a force can be exerted. Some are given (overleaf) in 'Suggested questions for homework or class'. These will enlarge pupils' knowledge as one pupil suggests things to others, and they will promote discussion.

If these questions prove really fruitful in promoting discussion, teachers may want to devote considerably more time to them – regarding the questions and discussions as a very important part of the teaching. That is why we suggest so many questions.

If you like, ask, 'Which is the force you feel: the force you use against somebody else, or the push of somebody else against you?' Do not continue into what would seem a very puzzling, and unnecessary discussion of Newton's third law at this point. This is a casual question to be left dormant.

Then give pupils an assortment of things – rubber bands, shirring-thread, a steel spring, a piece of thick rubber tubing to try forces on, a piece of latex foam for compression, and a piece of plastic foam for inelastic compression. These could all be in a small tray, containing the assortment for each pair of pupils.

66 Class Experiment
Stretching things

APPARATUS *item no.*

	From elastic materials kit:	*2*
	Expendable steel springs	*2A*
16	Soft rubber erasers	*2H*
8	Wide steel springs (about 15 × 8 cm diameter)	*2D*
8	Soft latex foam blocks	*2E*
16	Lengths of elastic cord	*2G*
	Foamed plastic	
	Ordinary rubber bands	

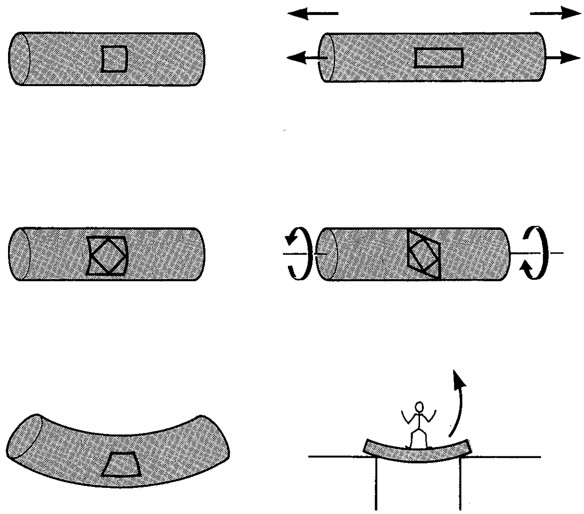
As the foamed plastic will be damaged easily, fresh pieces will be necessary for each class. The rubber erasers should be marked with ink patterns, preferably a set of squares.

PROCEDURE

Instead of judging forces by how far the pencil pushes into your cheek, or how much it hurts when some force twists your ear, have a look at forces doing things to rubber and springs. Fifteen minutes to find out anything you can, without other apparatus.

The *Pupils' Text* makes several suggestions as to procedure.

Then ask for things found out, of course taking suggestions from everyone in turn, not missing anyone out. Everyone will have found something about rubber and springs, force growing bigger with bigger stretch; the limit at which the spring gave way; plastic foam did not spring back; the marks on the rubber tube or cylinder showed what happened when it was bent, like a sagging plank being used as a bridge across a river. Someone may even have found what happens to the tube when it is twisted.



Ask if forces always get bigger and bigger when you go further. Asked in this vague way, the question will probably get the answer 'Yes'. If so, offer an experiment on the lecture table in which a load (a small bag of sand, or a 500-g mass) resting on the floor is attached to a cord which goes up and over a pulley held firmly so that pupils can pull it and go on raising the load while they pull the string a considerable distance. If there is time offer any unbelievers a spring balance for that.

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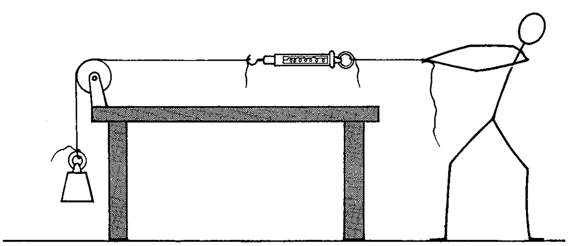
67 Class Experiment
A special case

APPARATUS *item no.*

1 Load of about 0.5 kg
1 Single pulley on clamp *40*
1 Spring balance (10 N) *81*
Cord *10A*



The horizontal arrangement is probably better than the more obvious vertical one in which the weight does get more difficult to pull down as it rises because the arm muscles are being used at a progressively worse mechanical advantage.

PROCEDURE

As above. With a fast group ask: 'How do you suppose the marks were put on this spring balance? Would you trust them? Could you test them?' (Leave those questions unanswered.)

Sometimes a force has no visible effect at all. Ask:

Suppose you sit on the table. Do you push on the table with a force? Does the table move? Does it go on moving? Does it stretch, or bend? Well, are you *sure* it doesn't stretch or bend? Suppose we made a table with a very thin plywood top and you sat on that? . . . Even with a thick table, I suspect, we should find that while you are sitting on it you make a dent in it, but it is a very small dent and you would need special apparatus to see how much you pushed the table down.

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

A. Kinds of forces. Friction forces. Gravitational forces.

This question to be answered orally, round the class.
Notes to teacher:
1. If some of these are too difficult, omit them.
2. If there are not enough to go round the class, go round again with the same questions but asking for different examples. The list below gives a number of ways in which a force can be exerted. For each of these *give*, in one sentence, *an actual example of the kind of force mentioned.* (For example, under **a** I might say 'e.g. when I start to walk I push backwards on the ground with my foot'.)

a. Motion: force exerted by something starting to move (or accelerating) e.g. . . . ?
b. Motion: force exerted by something slowing down (or stopping) e.g. . . . ?
c. Motion: force exerted by some moving thing whose direction of motion is being changed (without noticeable change of speed) e.g. . . . ?
d. Tension: force exerted by a stretched solid material, e.g. . . . ?
e. Compression: force exerted by a compressed solid, e.g. . . . ?
f. Compression: force exerted by compressed liquid, e.g. . . . ?
g. Compression: force exerted by compressed gas, e.g. . . . ?
h. Friction: solid moving over another solid, e.g. . . . ?
i. Friction: solid moving over, or through, a liquid, e.g. . . . ?
j. Gravitation: e.g. . . . ?
k. Electric: Force exerted by electric charges at rest, e.g. . . . ?
l. Magnetic: force exerted by magnets, e.g. . . . ?
m. Magnetic (or 'electromagnetic'): force exerted by current (in a wire) on a magnet, or one circuit on another circuit, e.g. . . . ?
n. Surface tension: force exerted by a liquid film or skin, e.g. . . . ?
o. Expansion: force exerted by something being heated, e.g. . . . ?
p. Contraction: force exerted by something allowed to cool, e.g. . . . ?
q. Any other sort of force that does not come under any of the above.

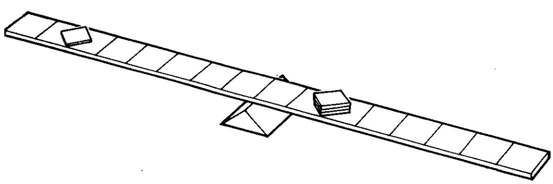
B.
Five effects, or results, that a force can produce are listed below. Copy the list and add one example to illustrate each, e.g. after **a** we might add 'A sailing yacht: the wind freshens and exerts a greater force (pushes harder) in the sails so that the yacht moves faster'.
a. Acceleration in a straight line: a force can start a body moving and increase its speed, e.g. . . . (give an example different from the one about the yacht).
b. Acceleration in a circle: a force can start a body rotating and increase its speed of rotation, e.g. . . . ?
c. Slowing down or stopping (of objects moving in a straight line or of objects rotating), e.g. . . . ?
d. Opposing other forces so as to keep a body at rest, e.g. . . . ?
e. Overcoming other forces so as to keep moving with constant speed, e.g. . . . ?
f. Deformation of size or shape or both, e.g. . . . ?

FORCES AND TURNING EFFECTS

68a Class Experiment
Turning forces on a seesaw

APPARATUS *item no.*
1 Lever kit *5*
This kit provides sufficient for pupils to work in pairs.

PROCEDURE
To balance the seesaw empty fix a paper-clip to the underside with a drawing pin and adjust the position of the clip until a rough balance is obtained. Instructions for this experiment are given in the *Pupils' Text*. Make it clear to pupils that an *exact* balance is not needed when they do the experiment, or some will spend too long worrying about it.



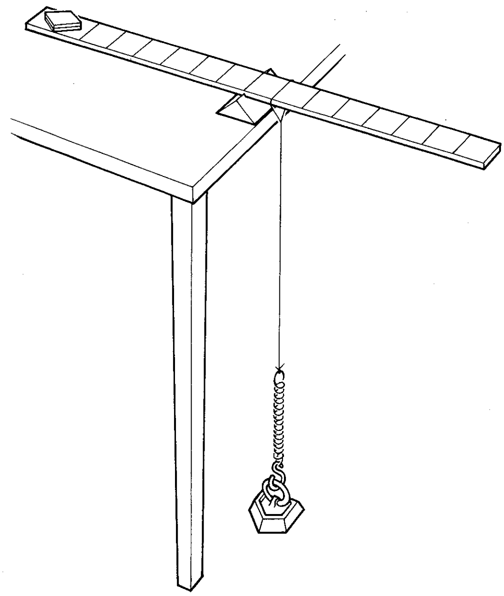
They have now constructed a weighing machine for weighing the force with which the Earth pulls down the left-hand load.

68b Class Experiment
A machine to measure the force of a spring

APPARATUS *item no.*
1 Lever kit *5*
16 Expendable steel springs *2A*
16 1-kg masses *32*
Cord *10A*

PROCEDURE
The pupils set up the experiment shown. They will need help in doing this and it is advisable to practice this so that hints can be given to them.

Since the lever is only a short distance above the bench top, it can only tilt a little, and the pull of the spring will be practically constant. To ensure this, the stretch of the spring must be large compared with the change when the lever tilts; therefore a weak spring is needed.



Adjustments to the tension can be made by altering the length of cord used in securing the springs to the lever or the anchor weight. Minor adjustments can be made by slipping exercise books between the floor and the anchor weight.

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69 Class Experiment
Qualitative ideas of the turning effects of forces

Give a demonstration of the turning effects of forces using, perhaps, a squeaky classroom door. Try pushing at the hinge, at the handle, and at intermediate distances. Ask whether a push or a pull has the same effect if you apply it near the hinges, half-way out, or all the way out.

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70 Class Experiment *(Optional)*

If a builder's jack is available, a heavy load (a boy, perhaps) can be placed upon it and raised by pushing gently on the side arm of the jack. The same question may be asked as in Experiment 69.

An alternative to a builder's jack is a chair containing a spiral support to adjust the height. It can be raised by means of a pole placed through its arms.

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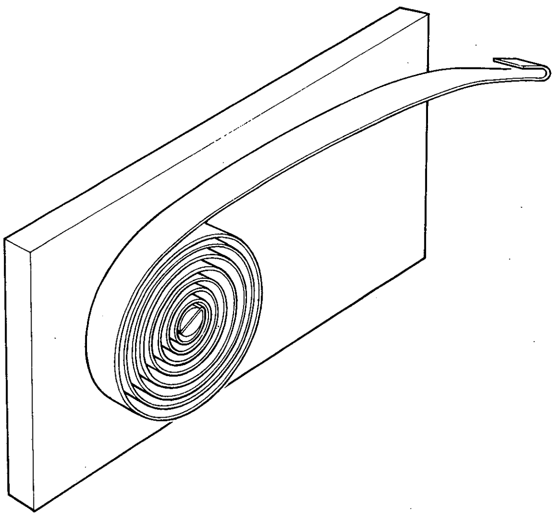
71 Demonstration
The giant clock spring

APPARATUS *item no.*

1 Large clock spring *57A*
1 Retort stand, boss, and clamp *503–506*

This large clock spring has been released into a large, flat spiral with one end fixed to a board. The board can be clamped vertically to a retort stand for convenience. The open arm of the spring can carry a load at different positions along it and the twisting effect will be seen. It may be necessary to prevent the load from slipping – small pieces of modelling wax are sufficient.



PROCEDURE

This qualitative experiment shows how, with the help of a spring, one could measure the effect of forces twisting something round an axle.

MAGNETS AND FORCES

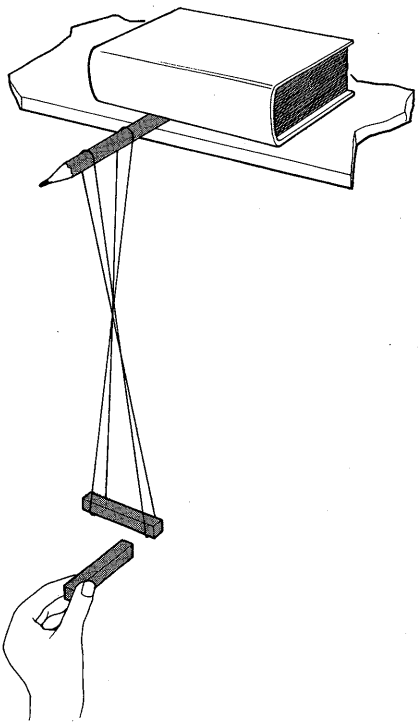
72 Class Experiment
Experiments with magnets

APPARATUS *item no.*

32 Pairs cylindrical magnets *50/1*
2 Horseshoe magnets *50/2*
1 'Eclipse Major' magnet *50/3*
Iron filings *555*
Nails
Compasses *556*

PROCEDURE

The main business here is to encourage simple play with magnets, so that children can feel the forces between them and know something about their behaviour for use in electrical experiments. The instructions are: 'Find out what you can about magnets. Have a good time with them.' Five minutes with some magnets would be too short: it would be irritating and muddling. Half an hour with magnets is probably enough. More than a whole period spent with magnets, making notes and perhaps giving special names to things, would be out of place at this stage. Note-taking would do more harm than good, by delaying things. If pupils ask, say: 'Yes, the places where the filings cling are called "poles".'



Encourage pupils to feel the forces between poles and to hang a magnet by a thread. Ask questions such as, 'Do the ends always attract each other? Try different ends on each other.' But do *not* give a formal statement about like poles repelling, etc.

The important thing to point out is that magnets exert forces when they are noticeably some distance apart, and bigger forces when closer.

If a big magnet is available, it may be placed on a central table as a 'pupil demonstration' for children to try things on. (Warn about watches.) It should not be shown as a formal demonstration to be seen on a remote lecture desk – that would be a poor example of action at a distance! – but individual experience will give children delight and knowledge.

(The question of North and South poles may crop up. It can be settled quickly by hanging up a bar magnet and showing that it does point roughly North and South. Say that we call the pole that points North the 'North-seeking' pole.)

Note on the 'North Pole paradox' Sometimes pupils get into a tangle about North and South poles when they learn that the Earth must be a big magnet and the pole up near the geographical North Pole must be the opposite type to a North-seeking pole. They waste time over the paradox that the Earth's North magnetic pole must be a 'South' pole. That is not a good scientific paradox that encourages thinking and makes people enjoy puzzling a problem out; it is merely a wrangle over wording which is best cleared up at once.

We call the end that points towards the North 'the North-seeking pole', since it points to somewhere near Alaska, where the Earth seems to pull it: the Earth itself must have the opposite kind of pole there. So the Earth's pole there is a South-seeking type of pole. You can keep it clear by calling those poles 'North-seeking' and 'South-seeking', and – this is a command – no one is to shorten those into plain 'North' and 'South' until he is quite sure that he knows what that means: that 'North Pole' is short for 'North-seeking pole'. Then there need be no puzzle just because the Earth does have, up in Canada, a South-seeking type of pole which might be called for short a South Pole.

73 Demonstration
Forces in collisions

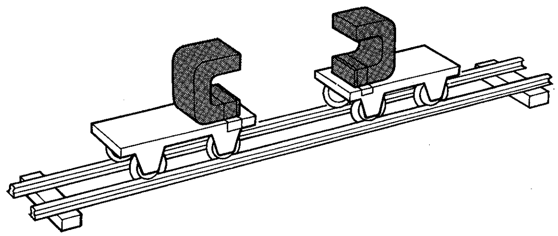
APPARATUS *item no.*

5 Lengths railway track *10R*
2 Flat trucks *10S*
2 Horseshoe magnets *50/2*
2 Wooden blocks with buffers *10T*

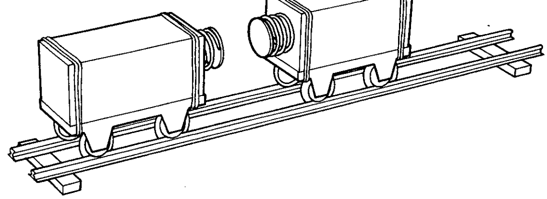
If necessary, the horseshoe magnets can be secured to the trucks with Sellotape and the wooden blocks with rubber bands. It may be necessary to counterbalance the magnets with weights taped to the other ends of the trucks.

PROCEDURE

a. Put the horseshoe magnets on toy train wagons on a section of level track, and then push one wagon towards the other stationary one, so that they collide with the repulsion between the magnets driving them apart. (If larger trolleys or roller skates are used instead of the toy train wagons, they may slew sideways in the collision so that the magnets will cling together, unless we compel the trolleys to run on rails or between narrow boundaries, such as strips of wood or metre sticks clamped to the table.)



b. Then show a collision with something else like buffer springs producing repelling forces instead of the magnets. Instead of the magnets, clamp to the front of each wagon a small piece of wood carrying a wide spring which projects out in front of the wagon and carries a disc as buffer on its outward end.



These collision demonstrations are important things for children to see; but at this stage, there should be *no* mention of momentum or of Newton's laws: simply a remark, 'Look at the kind of forces that can act in collisions.'

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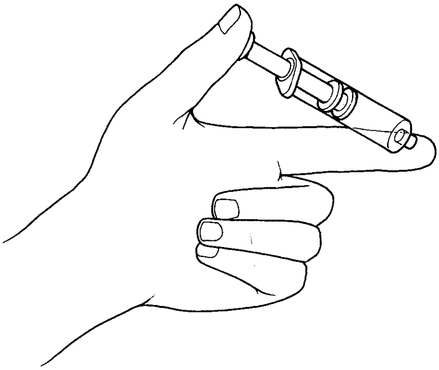
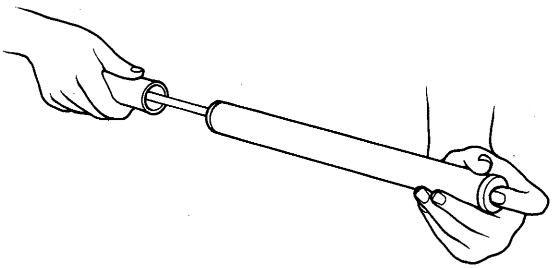
74 Class Experiment
Invisible collisions

APPARATUS
Bicycle pumps or syringes





In the case of magnetic repulsion, the pushing-away is rather like the push we feel when we drive the piston of a bicycle pump in with the outlet closed. In the pump we are pushing against molecular bombardments.‡

‡Microscopically these too exert electric forces.

CHAPTER 10
Electric circuits

Exploring and using electric circuits; making an ammeter and finding a law

Now we embark on a long series of simple class experiments with electric circuits using the Worcester circuit board. At this stage, work in the laboratory is in the nature of constructive play, with a large share of the planning done by the children themselves.

If the teacher draws circuits, any child can soon follow the drawing obediently without knowing what he is doing; and if the teacher gives a short talk before each experiment the work will proceed quickly and efficiently, but the children will miss a lot of the fun of doing experiments and they will not have built the capable lasting knowledge – 'I can make electric circuits work' – that they can gain from doing the experiments on their own.

These electric circuit experiments can profitably continue for several weeks. Only occasionally should we interpose a demonstration. Instruments, such as the home-made ammeter and then the commercial one, should come in as things to use and not, at first, as things with a mechanism to be explained.

Introductory comment to teachers Explain that we shall come back to forces and work and energy later in the year. (The pupils should have been through Year 1. Any who have missed Year 1 should be given an account of the discussion of forces and work and energy of that year.)

This raises a general question: the fate of things done and learned in earlier years. We should do all we can to suggest that the science pupils are learning will grow and that they will use the things they have learned before – that should not be a weapon to threaten, 'You must learn this and remember it', but we should use it as an encouragement, 'This is going to be important and useful later on'.

We shall now proceed to electric circuits, studied by class experiments. There are three reasons for spending time and trouble on electric circuits:

1. General importance in this electrical age.
2. In our physics we shall do a lot about atoms, and these pupils will need to know about electricity before they can understand experiments relating to the structure of atoms.
3. We have a whole lot of experiments with electric circuits that pupils can do on their own, so that they find what scientific work really feels like.‡

These are obvious reasons which all of us teaching would certainly have in mind; but we should also give these reasons to pupils if occasion arises – it is often good for the patient to know why he receives the medicine.

Class experiments with the Worcester electric circuit kit

We should do our utmost, particularly in early trial years of this part of the Nuffield Programme, to enable children to work on their own with this kit. That means that we must make sure they have enough apparatus to work in pairs, and we must give them plenty of time. Hurrying pupils through, to get an expected result or to 'finish the experiment today', will spoil things; time can be gained by some demonstrations instead of class experiments in another part of the course.

We must also be careful to give help and

‡ To encourage home trials by pupils as an important educational experiment, a small private fund is available to underwrite the possible loss or damage of apparatus while on loan. We hope that pupils will be able to take home a Worcester circuit board kit, a current balance, and perhaps electrolysis experiments. We hope even magnets will be taken home – despite their reputation for disappearing. Where a school lends such items of apparatus to a pupil to take home for experiments and finds that they cannot get them back or the apparatus comes back damaged or broken, they should apply to:

The J. Willmer Home Experiments Endowment,
c/o A.S.E.
College Lane
Hatfield, AL10 9AA

The General Secretary, administering this fund, will only ask whether the apparatus went on loan with permission, whether the class is following a complete year of our Nuffield Physics programme, what was damaged, and how much the cost. He will not want to know the name of the pupil and he will not want the usual formal details of a report of damage. The cost will be reimbursed most happily.

encouragement without giving 'cookery-book instructions'. For these young beginners, it would be useless just to provide an assortment of apparatus and no instructions. We certainly must tell them what to do, and what to do next, and next after that, and so on. But we do not need to tell them what to find, what to expect; nor do we need to tell them exactly how to carry out the experiment.

In the early stages of this series of experiments, pupils should not be given a complete outfit but only those things which they will need immediately. Extra equipment can be issued as needed; and later on extra equipment may be placed on a cafeteria table at one side for pupils to help themselves as they need.

For a clear story to emerge, it is important that the brightness of the lamps in each set of nine should match when each one is lit normally. This can be achieved if lamps from a single manufacturer (and preferably from a single batch) are used. Alternatively, lamps may be matched up beforehand. This is a simple matter if a board with three cells and nine lamp-holders is used for checking.

On the first day with the kit, the teacher must explain how the pegs and connectors are to be used and should point to the proper ends of the battery: but he should *not* draw circuits, nor even ask for notebook records yet.

75 Class Experiment
Lamps, batteries and circuits

APPARATUS *item no.*

16 Worcester circuit boards *52C*

Each group of two pupils needs:

3 U-2 cells *52B*
3 Lamps *52A*
12 Connectors *52E*
3 Connectors with lamp holders *52D*
2 Plug/croc leads *52I*

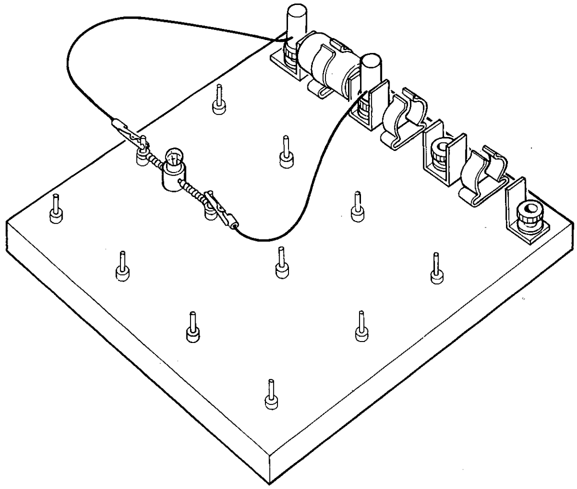
Later each pair will need:

1 Switch *52L*

PROCEDURE

Pupils follow these instructions:

You will need to have wires, or something else made of metal all the way round from the battery to the lamp (or whatever else you are using) and then back to the battery.‡ Try that.



a Make the lamp light.
b Then try turning the lamp round.
c Try turning the cell round.
d Try making a break, or using a switch, which is a thing to make a break.
e Try changing the connecting wires to make a different shape instead of a square. Does the lamp light just as well? Give pupils a sketch of a trapezoid.
f Try adding a second lamp, arranging things so that both of them light.

Leave the instructions for later variations alone, but move about among the children and encourage them.

g When you have done that, go back to one lamp and ask for a second cell. Connect up a circuit with two cells and only one lamp.
h Turn one of the cells round.
i Try two cells with two lamps.
j Turn one of the cells round.
Optional extra experiments include:
k Two lamps with three cells.
l Three lamps with two cells.
m Three lamps with three cells.

Where three lamps are lit by three batteries in series, *with one battery reversed,* we might ask a pupil, 'Does it matter in this case which of the three batteries is backward?'

‡ Teachers must decide whether to insist on using the name 'cell' or allow each cell to be called a 'battery'.

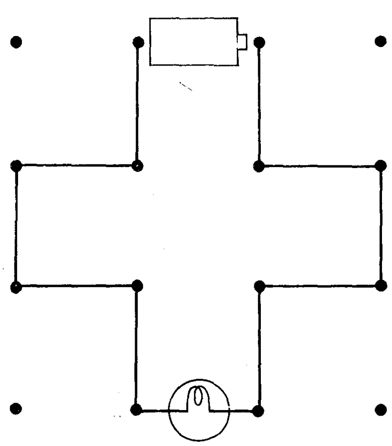
If in some of these experiments children say that they can see no light from a lamp, ask them to shield the lamp and look carefully for a very faint red glow.

Because of the time delay in manipulating components, the children may not notice the change from bright to 'half-bright'. If so, suggest using a crocodile lead for one of the battery connections so that a quick change can be made from one battery to two.

By now every pupil should have realized that a circuit requires a complete linkage all the way round, that a break will cause the lamp-lighting effect to stop. On the other hand, 'short cuts' (short circuits) may be undesirable. And the picture should now be building up that one lamp requires one cell, two lamps require two correctly connected, etc., for normal brightness, in this type of circuit. Suggest to children that they can use the brightness of a lamp as a measure of current‡

Suggestions for a work sheet to accompany Experiment 75

Try the following:
1. Connect a lamp to a cell and make that lamp light.
2. Try turning the cell round.
3. What happens if you break the circuit, or use a switch?
4. Try the circuit again but arrange it so that it is a different shape. Perhaps like this:



Does the lamp light just as well as before?
5. Try to light two lamps from the same cell.
6. What happens if you light *one* lamp from *two* cells?
7. Now turn one of the cells round, end for end.
8. Try two cells with two lamps.
9. Turn one of the cells round.

If some children say, 'This is getting too complicated to remember', we should reply:

You don't have to remember all these things that happen. Next time, I'll show you how to draw the arrangements easily. We shall call that 'drawing a circuit'. Then we'll make some kind of a record of what happens.

Lamps as informal ammeters

At an early stage of trying different arrangements of batteries and lamps, which will include such basic circuits as one battery lighting one lamp fully, the teacher should hold a short discussion with the children about using the brightness of a lamp as a measure of current.

Suppose you call a lamp 'fully lit' when it is connected to one cell. Have you ever seen a lamp that is extra bright? Have you ever seen a lamp that is duller than fully lit? Well, let us stick to the cases where the lamp is fully lit and call that one lamp's worth of current – whatever a current really is. Go on with your experiments, but later, when you make notes of what happened, I hope you will be able to say how big some current was, reckoned in fully-lit lamps' worth.

Where this is done it is most important that the individual lamps used in a circuit should appear equally bright.

Heating effect

At this point, the teacher should give a short discussion:

This is one of the things that electricity does: something happens when we join the battery with metal to the lamps that makes the lamp filament hot. When you go back to your experiment, try that with a short piece of very thin bare wire and see whether the electric effect makes that hot. . . . That is one of the things that an electric current does (why we call it an electric current will be clearer later).

‡ The Worcester circuit board does not encourage putting cells in parallel. Nor should we encourage that in modern teaching – it is a relic of days long ago when cells had large internal resistance; and it is not done now. On the other hand, generators are connected in parallel – an essential and dangerous operation – in modern grid systems. And lamps in all home lighting are in parallel. Pupils should certainly learn about lamps in parallel.

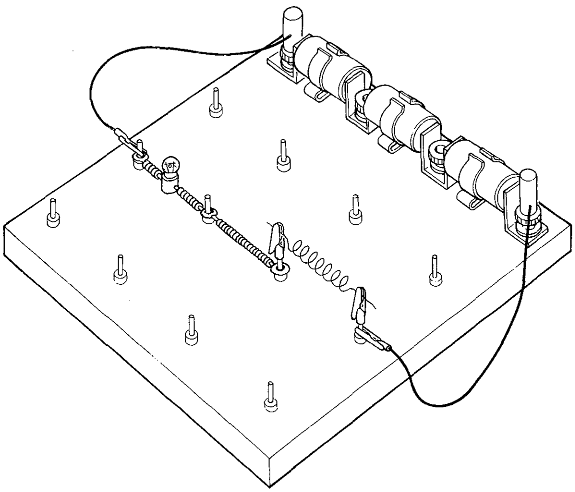
76 Class Experiment

Heating effect of a current

APPARATUS *item no.*

16 Worcester circuit boards *52C*
1 100-g reel bare Eureka wire 34 SWG *52P*

Each group needs:
3 U-2 cells *52B*
1 Lamp *52A*
2 Crocodile clips *52K*
4 Connectors *52E*
1 Connector with lamp holder *52D*
2 Plug/croc leads *52I*



PROCEDURE

Wind a 50-cm length of bare Eureka wire into a coil (perhaps on a pencil). Slip the shanks of two crocodile clips over adjacent pillars and use the clips to support the coil. Thus introduce the coil into a series circuit of three cells and a lamp.

Magnetizing

Children will have found magnets picking up iron filings or chips of iron in the first lesson on forces. Explain that: 'This "magnetic effect" is another thing that electric currents will do. And there are some other, different, things that currents will do. And these things are all we really know currents by.'

77 Class Experiment

Making an electromagnet

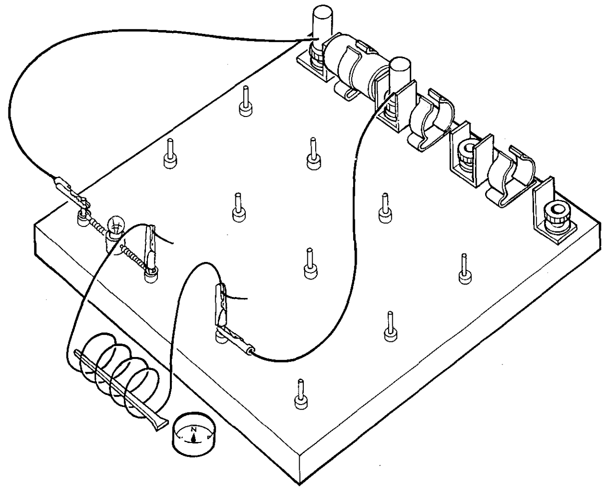
APPARATUS *item no.*

16 Worcester circuit boards *52C*
Compasses *556*
Iron filings *555*
Connecting wire

Each group needs:
1 U-2 cell *52B*
1 Lamp *52A*
4 Connectors *52E*
1 Connector with lamp holder *52D*
2 Plug/croc leads *52I*
2 Croc/croc leads *52J*
1 Iron nail *52M*

The connecting wire should be about a metre of insulated copper wire, about 26 SWG.

The iron nail should be 5 to 8 cm long and made of soft iron. Such nails are included in the circuit board kit.



PROCEDURE

Pupils should wind the length of wire into a long, tight coil, on a pencil or dowel, into which the nail can easily slip. Using the croc/croc leads, connect the coil into a circuit of one cell and one lamp so that it is conveniently near the plotting compass. Try the nail first on iron filings and then with a compass.

Should the effect be too small, it can be increased by dispensing with the lamp in series.

NOTES

1. Many nails are weakly magnetized before the experiment commences and any that are should be weeded out or demagnetized before the pupils get them.

2. To demagnetize the nail at least 500 ampere-turns are needed. A Unilab 250-turn coil on 6 V a.c. takes 3 A (giving 750 ampere-turns) and a Unilab 500-turn coil on 12 V a.c. takes 2 A (giving 1000 ampere-turns). These are both suitable for demagnetizing nails, but should not be left on for long as the coils get hot (about 18 and 24 W respectively). The nail is put inside the coil which is connected to an a.c. low-voltage supply at 6 or

12 V as stated above. The nail is slowly removed from the coil – any motion other than a sudden jerk will be slow enough. Or the alternating voltage supply may be steadily reduced to zero.

Measuring current: making a simple 'current balance'

If heating and magnetism are all we know about a current, we must judge it that way. You were very sensible to use the brightly lit lamp to tell you that you had a current of some definite size. Now, we are going to try to use the magnetic effect of a current. You can make a little machine to show how big a current you have.

Show the arrangement of the Worcester 'current balance'. Then the children should make it. The assembling will take time – at least one period – but the whole point of this is to let children make the meter and adjust it themselves, whatever the cost in time.

78a Class Experiment
Making an ammeter

APPARATUS *item no.*

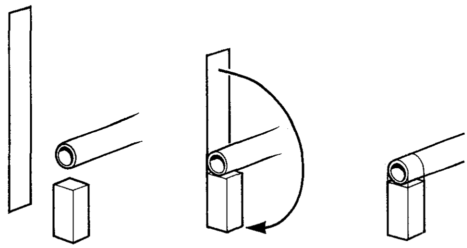
16 Worcester circuit boards *52C*
1 Worcester current balance kit: *53*
Base assembly with coil *53C*
12-mm Alcomax magnet *53B*
Drinking straw *53A*
Sewing needle *53D*
Rider of tinned copper wire *53H*
Wooden strip (15 × 2 cm) *53F*
Wooden block (4 × 4 × 2 cm) *53E*
Sellotape *53I*
1 Reel 26 SWG bare copper wire *2C*

Each group needs:
3 U-2 cells *53B*
3 Lamps *52A*
Connectors *52E*
3 Connectors with lamp holders *52D*
4 Plug/croc leads *52I*

ASSEMBLY OF CURRENT BALANCE

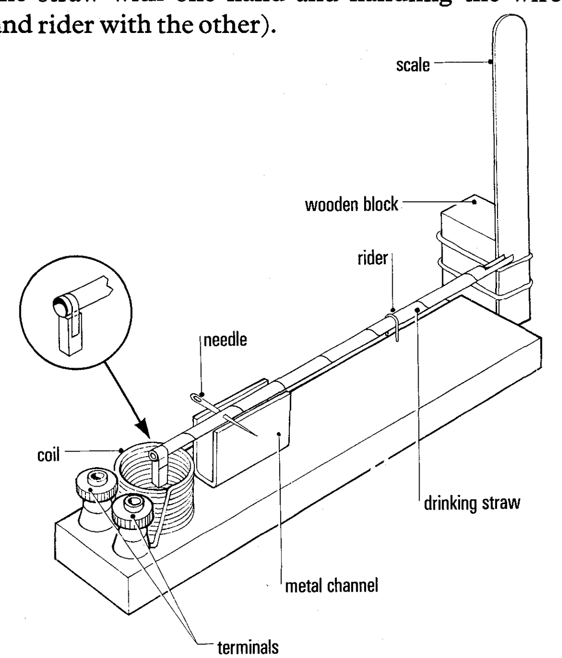
1. The pupils should fasten the 12-mm magnet near to the end of the drinking straw with about 4 cm of Sellotape. Perhaps the easiest way is to cut the Sellotape, attach it to the magnet and fix the drinking straw as shown.

2. Balance the straw *on* the needle to find the centre of gravity of the straw with the magnet attached. Stick the needle through the straw a very little farther away from the magnet (not more than 1 mm from the centre of gravity of the combined straw and magnet). Only as a remedy in the face of disappointment should pupils be given these details as instructions. Instead, the teacher should give extra straws and encouragement.



Then with the magnet near the centre of the coil, the needle is about 5 mm from the end of the metal channel. The straw should be horizontal when the magnet is vertical.

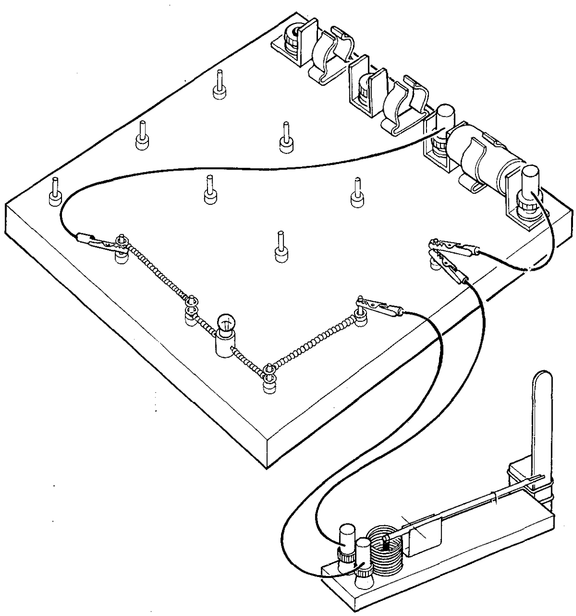
3. The rider is made by wrapping 2.5 cm of 26 or 28 SWG copper wire round a pencil and is slipped over the straw. The rider should balance the straw horizontally when it is not more than 5 cm from the needle. If it has to be nearer the free end of the straw, the range of the current balance will be reduced (though not the sensitivity). For the more clumsy pupils it may be better to use up to 5 cm of 26 or 28 SWG wire for the riders. This will make the balance less sensitive but the position of the pin will be less critical. Provide a short length of the same wire to use as a 'lifter' when adjusting the position of the rider (best done by steadying the straw with one hand and handling the wire and rider with the other).



The straw should rest horizontally and a reference mark should be made on the wooden strip, attached to the wooden block provided, positioned at the end of the straw.
4. Check that the coil does not obstruct the free motion of the straw.

NOTES ON USE
1. The leads with a 4-mm plug on one end and crocodile clips on the other end are the most convenient for connecting the balance in the circuit. These are provided in the circuit board kit (item 52I).
2. If the straws give trouble by slewing round, cut a shallow groove accurately in the vertical rails with a file to localize the straw.
3. Beware of draughts. (Warn pupils not to wait for the straw to come to rest.)
4. The balance is best placed to one side of the board.
5. The magnet/straw assemblies are quite fragile and care should be taken to preserve them between lessons.

PROCEDURE
Pupils assemble their own balances, working in pairs.



They try this meter in circuits in which they know the current is 'one lamp's worth'. It is better to avoid moving the rider along a scale of currents, and just keep it at 'one lamp's worth'. Then pupils can classify currents as more or less than that.

78b Class Experiment
Using the current balance

Without moving the position of the rider on the balanced arm, add a second lamp in series with the first to provide a current which is less than 'one lamp's worth'.

78c Class Experiment
Stronger battery

Still with the rider set to measure 'one lamp's worth', try a circuit with one lamp and two cells so that the current is 'more than one lamp's worth'.

79a Class Experiment
Current at different places in a circuit

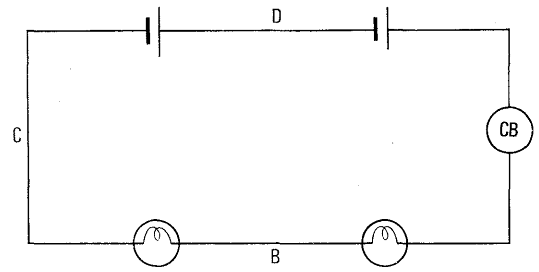
APPARATUS *item no.*
Each group needs:
1 Worcester circuit board *52C*
2 Cells *52B*
2 Lamps *52A*
2 Connectors with lamp holders *52D*
Connectors *52E*
4 Plug/croc leads *52I*
1 Croc/croc lead *52J*
1 Assembled and working current balance

PROCEDURE
This is an extremely important experiment. Ask pupils to try putting their current balance in different places in the circuit.

Take two lamps and two cells and connect your current balance in this circuit in a number of different places, between the lamps, between the cells, between the cells and the lamps. Each time, notice the reading. What does this experiment tell you?

The result may well be surprising, because this idea of resistance is there in common talk, and many people think the current will come out of the lamp smaller than it went in. Even when pupils have seen this for themselves, they will sometimes forget that the current is the same all round the circuit. If we want them fully to appreciate this very important property, we must leave them to absorb it, and not dictate it as obvious knowledge from the teacher.

Pupils should connect up the circuit shown and adjust the rider for balance. Then, without touching the rider again, the current balance should be connected into the circuit first at B, then at C, and at D.



79b Class Experiment
Using an ammeter

APPARATUS *item no.*

In addition to the apparatus listed in Experiment 79a, each pair will need:

1 d.c. ammeter (0-1 A) *79*

PROCEDURE

Experiment 79a, in which the pupils investigate a current at a number of points in a series circuit, is repeated but with the ammeter replacing the current balance.

Notebook records Up to this point, a careful recording of experiments in a notebook would have two disadvantages: first, it would delay the experimenting so much that some children would lose the thread; second, it would make the children ask what to record and how to record it and bring the teacher into the business, and thus spoil the atmosphere of open experimenting. Now, however, when some skill and some half-understood knowledge have been acquired, the teacher should give a blackboard talk on how to draw circuits neatly, and how to show lamps and batteries, etc., by symbols.

Then he should ask the children to draw in their notebooks the circuit for a battery and a lamp, then two batteries and a lamp, then two batteries and two lamps, and so on. Then the pupils should try what happens in each of those circuits, all over again, and make a very short note of what they see.

It is much quicker, but not nearly so good, if the teacher draws all these circuits on the blackboard. At a later, much more sophisticated, stage a drawn circuit is simply a quick piece of codified communication between teacher and pupils; but at this stage it is nearer to the teacher doing the thinking for the pupils; so it is better to let them draw their own circuits. Drawing neatly with rulers will take more time than is justified: the drawings should be neat but not meticulous.

'Direction of current' The circuit board is useful in predicting where the red and black leads should go to in the circuit and then showing that the prediction does in fact give a downward pull. Of course the current balance does not tell us which way the 'electricity' really moves: but it does provide an arbitrary reference standard.

Discussion of current Then we say:

There *is* something the same all the way round the circuit, the same reading with this simple ammeter, or the same brightness of lamp.

(One of the two lamps can be moved to a place between the two batteries in series and will still be just as bright.)

That is why scientists say 'There is a current; there is something running round the circuit which stays the same all along, just like a current of water in a river.' If a river is carrying 1000 gallons a minute past one place, it must be carrying 1000 gallons a minute past any other place farther down the river – unless there is some side-stream, or a mysterious hole in the ground. Some scientists like to think of this electric current story as rather like water being pumped round a closed ring of piping.

The teacher continues with a description of a water circuit and shows a model, and points out that the flow would be the same all round.

80 Demonstration
A water circuit

APPARATUS *item no.*

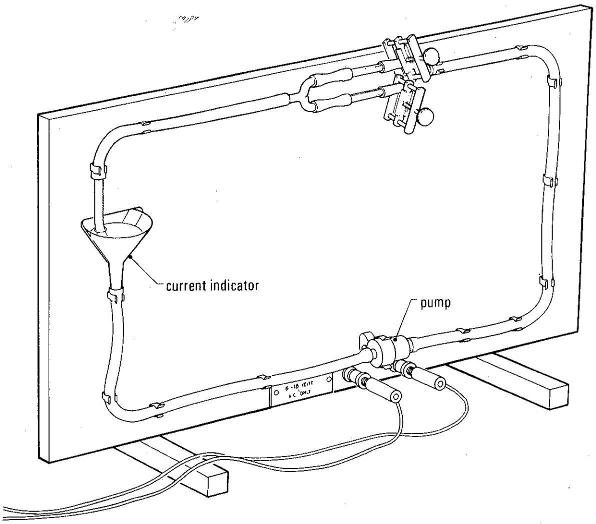
1 Water circuit board (without pressure gauge) *89*
1 L.T. variable voltage supply *59*

PROCEDURE

The water circuit board should be set up vertically. The tubes should be filled with water: a little fluorescein or a few drops of methyl orange can be added to make the water more clearly visible. The water is conveniently poured in at the funnel – see illustration. (At this stage, a pressure gauge should *not* be used.) The two tubes which lead through the back can be used to help overcome difficulties with remaining air bubbles.

Sufficient water should be used just to cover the outlet tube of the 'flowmeter' which should be inclined so that the water in the funnel will swirl round when the water current flows.

A small piece of polystyrene (about 5 mm cube) is put in the water in the funnel. The speed at which it swirls round is an indication of the strength of the current.



The electric motor – which acts as the water pump – should be connected to the a.c. terminals of the L.T. variable voltage supply (*not d.c.*). The motor can in fact be operated up to 18 V, but it is recommended that the voltage should not exceed 12 V. The pump drives water round the circuit of the tubing, the pressure being dependent on the voltage applied to the motor.

In some models, the tube divides at one point. The two sections represent different resistances; one is empty, the other contains foil or glass wool. The former tube should be closed with a clip during this demonstration.

The teacher may ask:

Is there really something that moves round through the copper wires and through the lamp, and makes the lamp light or pulls the magnet?

As far as you or I can tell now, we can only say 'This electric behaviour is *rather like* the behaviour of a current of water flowing, that makes the same thing happen all the way round. But we do not know whether anything is really flowing, and certainly not what it is.' If it flows it might be some kind of 'juice' flowing this way round the circuit, or it might be some opposite 'juice' – we should say negative instead of positive electricity – running the other way round the circuit. Or there might be both of those, each running its own way.

Instead of some smooth 'juice' flowing like water in a pipe, the current might be a movement of little particles, little bits of electricity, moving along like a line of rabbits in a burrow or an army on a road. Again, this might be a row of positive bits travelling this way, or negative bits travelling that way; or both kinds, each travelling its own way.

Which of all these things do you think is right? Nothing travelling at all, or 'juice' travelling one way or another, or little bits of electricity travelling one way or another?

Whatever the answers – which the teacher should accept quite happily at this stage – the teacher should say:

We must wait for further evidence. Nowadays, we think we know that there are things that move when an 'electric current' happens, in some cases several kinds of things; but we cannot show you that yet.

(In fact, contrary to wishful hopes, nothing we do in elementary physics teaching – even though we include cathode ray demonstrations and a photo-electric experiment – requires a view that electric charges come in small particles. Continuous (negative) juice would do just as well! Only when we come to Millikan's experiment do we meet clear evidence that requires 'particles' of electric charge.)

For the moment we shall stick to the standard agreement, used by all electrical engineers, which is the idea of bits of positive electricity coming out of the red knob of the battery and going round the circuit in one direction to the negative end of the battery.

That was settled long before anybody knew about 'electrons'; and now that agreement, which is used to put arrows on the electric circuit drawings, is used so much that it would not be safe for us to make a muddling change. Later on, you will be able to decide for yourselves what is really going on – and you may find it even more complicated than you think.

Parallel circuits

81a Class Experiment
Currents in parallel circuits

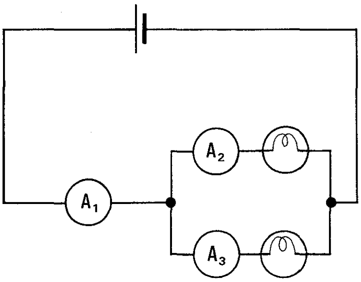
APPARATUS

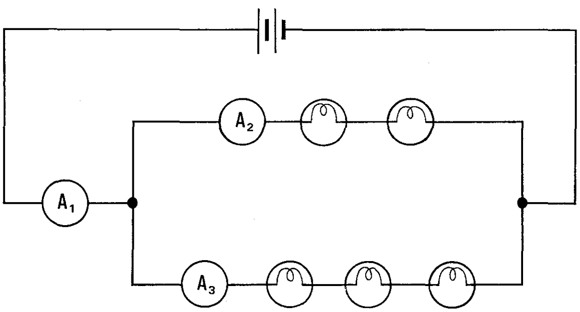
16 Worcester circuit boards *52C*
16 d.c. ammeters (0–1 A) *79*

Each group needs:
3 U-2 cells *52B*
7 Lamps *52A*
7 Connectors with lamp holders *52D*
Connectors *52E*
4 Plug/croc or similar leads *52I*

PROCEDURE

Pupils set up the two circuits in turn and take readings of the ammeter when it is connected in each of the positions A_1, A_2, and A_3. They should be asked for a rule relating the three readings in each case.

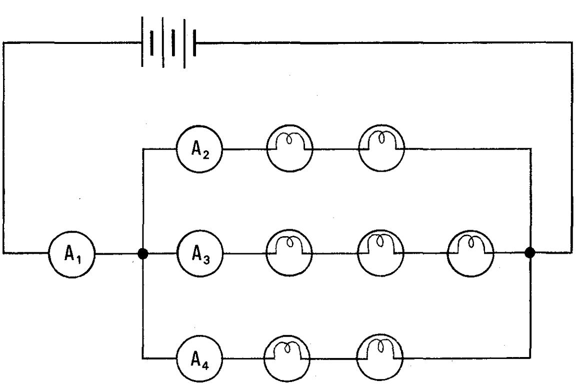




81b Class Experiment
Applying the rule

APPARATUS
As for Experiment 81a.

PROCEDURE
Pupils set up a third circuit and take readings of the ammeter when it is connected in positions A_1, A_2, A_3, A_4. 'Does the rule discovered in Experiment 81a apply?'

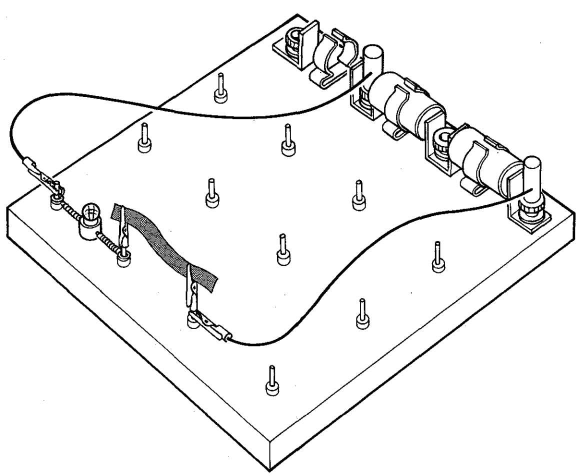


CURRENTS AND CONDUCTORS: RESISTANCE

82 Class Experiment
Trying various materials in circuits

APPARATUS *item no.*
16 Worcester circuit boards *52C*
16 d.c. ammeters (0–1 A) *79*
Each group needs:
3 U-2 cells *52B*
1 Lamp *52A*
2 Crocodile clips *52K*
Connectors *52E*
1 Connector with lamp holder *52D*
2 Plug/croc leads *52I*
2 Croc/croc leads *52J*
1 Connector with rheostat *52F*
1 Resistor *52H*
1 Diode *52G*
Miscellaneous materials, such as a piece of wood, a strip of paper, a strip of copper, a thread of nylon, aluminium foil, pencil lead (preferably a soft grade), bits and pieces from pupils' pockets, and about 50 cm of Eureka wire (SWG 34, 0.25 mm) as used in Experiment 76.
Some fine steel wool (grade 2)
2 Fuse links (19 mm rated at 0.25 A)

PROCEDURE
Using two cells only in the board, pupils should insert various samples of materials in a circuit to see if they will carry current. Crocodile clips with their shanks slipped on adjacent pegs of the circuit board can conveniently hold the samples in the circuit.

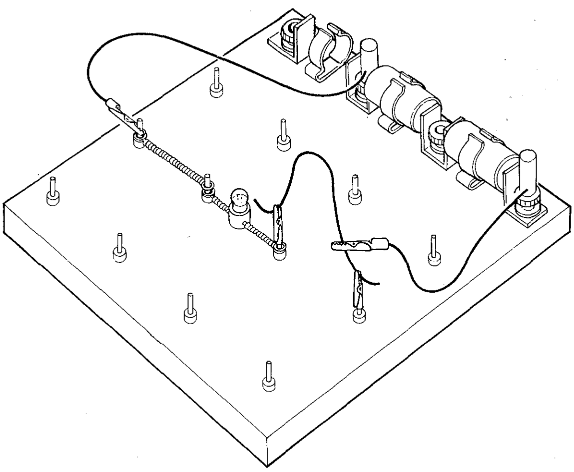


Point out that the 50-cm length of thin wire used in Experiment 76 made the lamp glow dully; it seemed to resist the flow of electricity.

83 Class Experiment
Making a variable resistor

APPARATUS
As for Experiment 82.

PROCEDURE
Using the same circuit as in Experiment 82, pupils clip one end of the 50-cm length of resistance wire into one of the crocodile clips and the other end to a croc/croc lead which is then connected into the circuit. They should vary the length of wire between the two clips and observe the effect on the lamp. Then they insert the ammeter in the circuit and repeat.



84 Class Experiment
Using a variable resistor

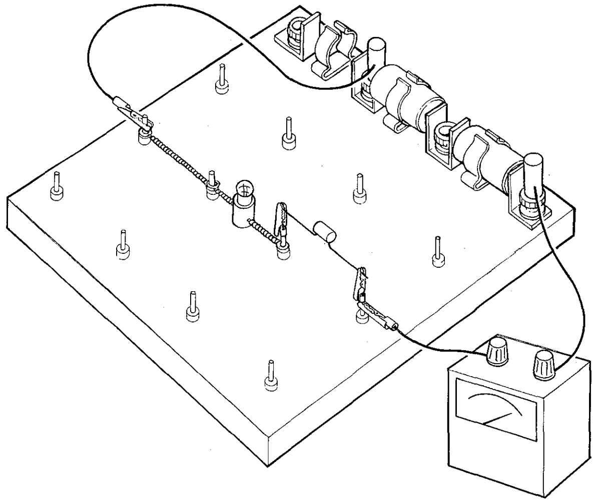
APPARATUS
As for Experiment 82.

PROCEDURE
Pupils should make the lamp dimmer and brighter using the variable resistor (item 52F) in the circuit.

85 Class Experiment
Testing a radio resistor

APPARATUS
As for Experiment 82.

PROCEDURE
Pupils should try the radio resistor between the two clips in the circuit; then turn it round, end for end.



86 Class Experiment
Testing a diode

APPARATUS
As for Experiment 82.

PROCEDURE
Pupils should try the diode between the clips, watching both the lamp and the ammeter. Then they turn that round, end for end.

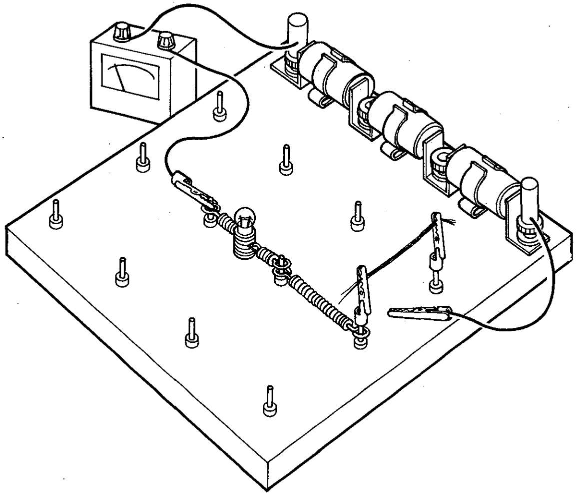
Resistance and temperature

In switching on a lamp with an ammeter in the circuit, some pupils may have noticed that the current is momentarily bigger at the start. And as we know, any attempt in later experiments to look for a simple linear relationship between current and voltage fails for electric lamps. We know that metal wires do obey Ohm's law; and we know that the simple behaviour is obscured by temperature changes. We should not teach that at this stage; but we should let pupils find that there are considerable changes of resistance when the temperature of a (pure) metal is changed. For that, offer them a fine piece of iron wire, taken from steel wool.

87 Class Experiment
An experiment to think about

APPARATUS
As for Experiment 82.

PROCEDURE
Using three cells in the circuit, pupils clip a few

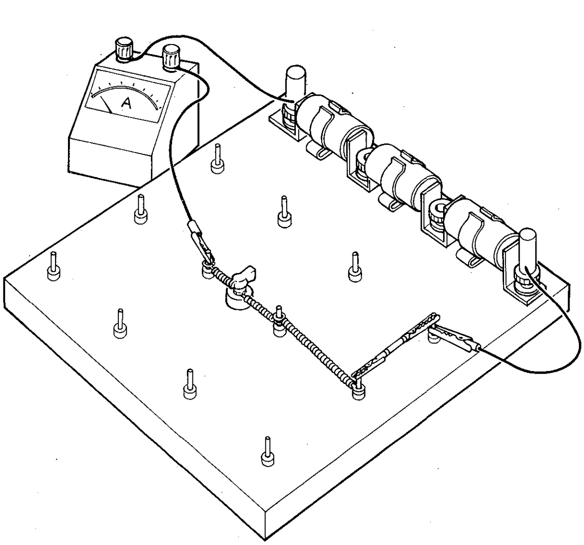


strands of fine steel wool into the circuit. The lamp will tell whether there is a current flowing or not. When there is, they short-circuit the lamp and observe the ammeter. Then they blow gently across the steel wool and observe what happens to the ammeter reading. Ask what is happening to the resistance of the steel wool when it gets warm.

88a Class Experiment
A fuse

APPARATUS
As for Experiment 82.

PROCEDURE
Then they use a flying lead to shorten the length of the wool in the circuit to about half and observe what happens.



88b Class Experiment
Testing a fuse link *(Optional)*

APPARATUS
As for Experiment 82.

PROCEDURE
Pupils connect three cells in series with the fuse link, the ammeter and the variable resistance (item 52F). Gradually they decrease the resistance in the circuit, watching the current reading in the ammeter until the fuse blows.

Note: 'resistance' as the name for a constant Resistance is a word that comes from the water-flow analogy. That idea was so strong in Ohm's mind when he started on his researches that he said he was looking for electrical 'resistance' and trying to find its properties. When it was found that wires give a constant ratio for p.d./ current, that constant was given the name 'resistance' which Ohm had ready for it.

In contrast with this one case, the order of events in most physical discoveries is the other way round; we first discover experimentally that some ratio has a constant value and then coin a name for it because it is constant, e.g. we find the ratio [stress]/ [strain] constant for a wire and then call that Young's modulus.

Sometimes when we are teaching, this logical order gets obscured: some pupils grab the name of the constant and somehow take it for granted that the name itself assures the constancy and thus takes away any need for experimental investigation. Then the practical experiment becomes a scheme for making one accurate measurement of that assured constant instead of an interesting investigation to see what relationship is there. Examples: single measurements of resistance, Young's modulus, '*J*', specific heats. Of course, there is nothing wrong in making these measurements: each has its importance in professional physics; but an organized series of such experiments can give beginners a wrong-headed picture of science.

We shall not deal with Ohm's law until Year 4, and even then only briefly, for this is the transistor age, in which *non-linear* devices are of great importance.

Comment on notebooks At this stage, a pupil's notebook should have a drawing of each circuit –

neat *but not meticulously ruled*–and a note *in his own words* of what happened.

There should be no pressure, in these experiments, to draw conclusions. These young people are getting acquainted with electric circuits, and we hope they are enjoying that and building up some sense of knowing their way around among electrical things. Insisting on formal conclusions would be artificial and puzzling; and in many cases the teacher would have to end up by dictating a conclusion. After all, when you have been to the circus and come home and have given a glowing but inaccurate description of it, the only *conclusion* that could be added would be, 'I enjoyed it'.

Encouragement Those of us who have not tried teaching elementary electric circuits with young pupils working on their own like this will be surprised at the difficulties and the delights. Trying things that seem obvious and quick to us will take the children much more time. And the simplest and most obvious mistakes seem to make them feel puzzled–then they need encouragement, but not always quick help in putting things right. Simple experiments that seem to us dull and obvious seem to them a delightful part of growing knowledge.

Plugs, wires, and earthing

Experiment 88a provides a useful opportunity to examine a mains plug, its fuse and the wiring between the plug and such an appliance as an electric kettle. The function of the fuse can be considered and the 'earth' connection can be discussed.

COUNTING THE CELLS: VOLTMETERS

(To be omitted by slow groups)

In Year 3, we shall introduce voltmeters as empirical instruments and in Year 4 we shall use them with a clear definition of potential difference, in terms of energy transfer, but we can with faster groups give a first hint now of voltmeters and their uses as follows.

89 Class Experiment

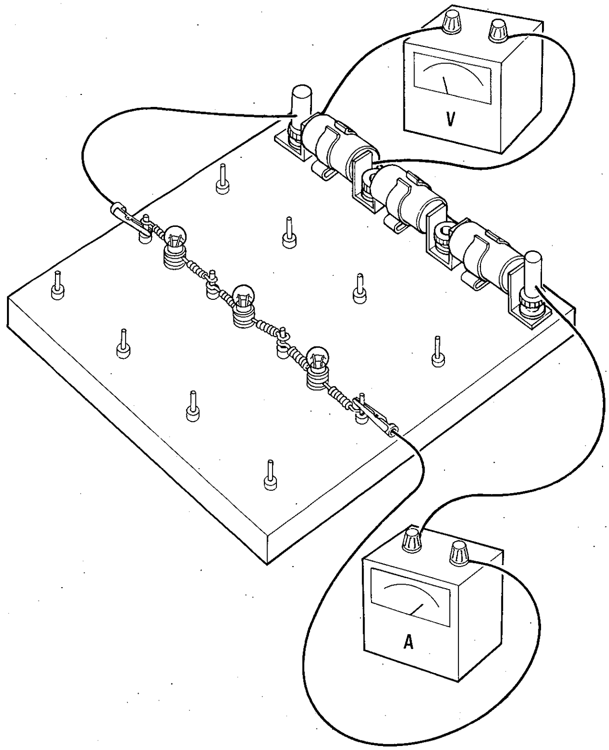
Using a voltmeter as a cell counter *(Optional now)*

APPARATUS *item no.*

16 Worcester circuit boards *52C*
16 d.c. voltmeters (0–5 V) *80*
16 d.c. ammeters (0–1 A) *79*
Cinemoid filter (frost) *57J*

Each group needs:

3 U-2 cells *52B*
3 Lamps *52A*
3 Connectors with lamp holders *52D*
3 Plug/croc leads *52I*
2 Croc/croc leads *52J*



PROCEDURE

Ask the pupils to set up the circuit with three lamps and three cells with an ammeter in series. At this stage, it is fair to draw the circuit on the board or on the pupils' worksheets, because the problem is not to get this circuit set up and understood but to set it up quickly so that it can be used in the examination and understanding of something much more difficult. Then ask the pupils to connect two leads to the terminals of the voltmeter and then to put that instrument across (i.e. in parallel with) one cell, then two and finally all three cells.

How many cells are needed to run one lamp? How many cells are needed to run two of your lamps together? How many cells are needed to run all three lamps? *This new instrument is counting something for you.* What does it count?

We hope to elicit the idea that this new instrument acts as a 'cell counter'. It counts the number of cells in use for the particular lamp or group of lamps that we apply it to.

NOTE

If teachers prefer the voltmeters to be uncalibrated for this experiment, this is easily achieved by cutting a piece of Cinemoid filter (No. 29 or 31, frost) to the shape of the scale and then fixing it in position over the front window with Sellotape. This will carry pencil markings. A supply of Cinemoid filter is included in the Year 2 general kit (item 57J). Alternatively, 'write on' Sellotape can be used.

COUNTING IN SCIENCE

We shall have described an ammeter as a counter of lit lamps (in parallel); and some fast pupils will now meet our description of a voltmeter as a counter of cells (in series). If pupils comment that counting is a queer job for an electrical instrument like this, we should treat this question gently and use it as an opportunity for a very general piece of science teaching.

We often have to count when we make a measurement in science. Suppose I measure the length of a piece of paper with a centimetre scale. I just put the edge of the scale against the paper, move the scale till the top of the paper is at nought and then I see the bottom of the paper is at 20.6 cm, so I say the length is 20.6 cm. But I could do it like this: I could get something just 1 cm long and mark 1 cm from the top of the paper to this mark, and then 1 cm again, and then again, and so on, like a man pacing off a distance in paces. Then all I have to do is to count the number of times I mark off another centimetre on my way down the sheet. Of course, when I come to the end there is a bit left over and then I had better mark 1 mm, and then one more, and so on, and then count how many millimetres.

What does a clock really do when it keeps track of the time for you?

Elicit the answer that somehow the clock counts seconds and does that, if it's an old-fashioned pendulum clock, by counting swings of the pendulum. Ask what a watch does. If the question of electric clocks crops up, ask whether they too count something, not swings of a pendulum but perhaps swings of the electric current to and fro to plus and minus. (And we might go further and suggest the clock counts revolutions of the dynamo.)

Yet we point out that ammeters do not seem to be counting anything in the wire.

The ammeter seems to just measure a steady force when there's a steady current; but if it were a current of water, you could certainly measure by counting how many litres go past any point that you watch, in every second, or every hour. (In fact river-flow is measured in thousands, or even millions, of litres per hour.)

Is there anything corresponding to that with ammeters?

(Wait for electrolysis to offer an answer to that.)

Buffer experiments

We hope that in the series of experiments with the Worcester circuit board pupils will be able to go on at their own pace, some moving ahead fast and others even going back to repeat an experiment that they did not understand. Any such plan raises difficulties in running the class; and we therefore suggest to teachers that they should have 'buffer experiments' up their sleeves for abler and faster pupils to do while others are catching up. Such buffer experiments will give faster pupils new things to think about and do. A few are suggested below.

89X Class Experiments
Investigating circuits *(Optional)*

APPARATUS *item no.*

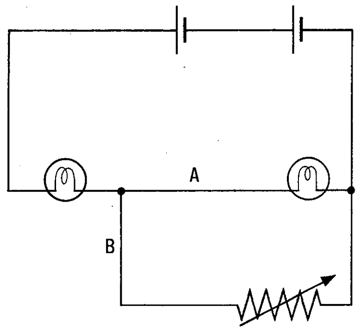
Each group needs:

1 Worcester circuit board *52C*
3 U-2 cells *52B*
5 Lamps *52A*
5 Connectors with lamp holders *52D*
2 Plug/croc leads *52I*
2 Croc/croc leads *52J*
1 Spring connector with rheostat *52F*
Spring connectors *52E*
1 d.c. ammeter (0–1 A) *79*

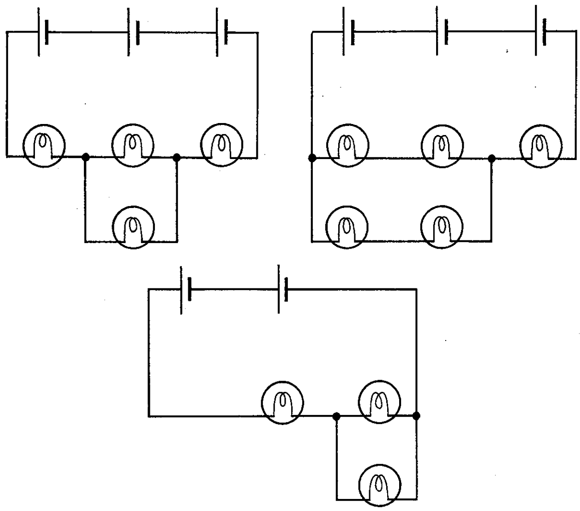
PROCEDURE

There are a number of additional circuits which faster groups of pupils might investigate.

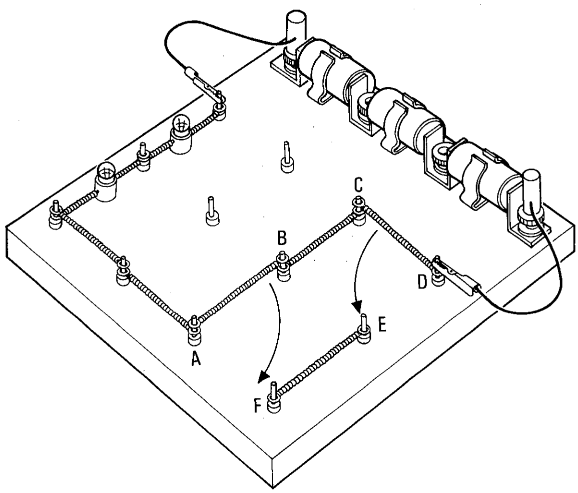
a. First, an ammeter is placed at A and the resistance of the rheostat varied. The ammeter is then moved to B and the experiment repeated.



b. To assist in making the distinction between lamps connected in series and lamps connected in parallel, circuits of the type shown can be examined:

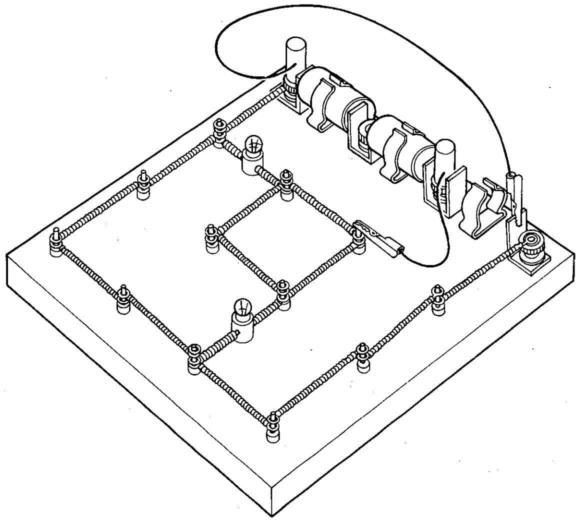


c. Two-way switching using two loose links as switches can be investigated.



The circuit is set up as illustrated using three cells and two lamps in series. A free link is attached to A and another at D, so that these represent switches. If A is connected to B and D to C, the lamps light. The circuit can be broken at either switch by changing A to F or D to E. The lamps can then be switched on again at either switch.

d. The ring main can be investigated as follows:



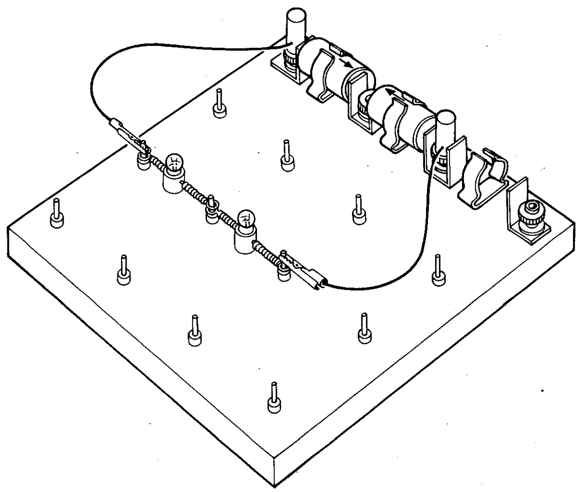
e. Problem circuits can be suggested such as using two cells to light four and then six lamps fully. This can be followed by the lighting of three, then six, then nine lamps using three cells.

(Result in these cases should be tabulated under headings:

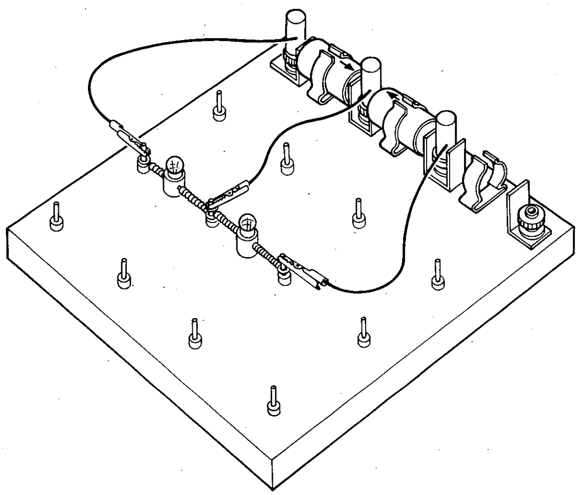
No. of lamps fully lit	No. of cells used	No. of current units

A relationship can then be sought.)

f. Set up the circuit shown. Why do the lamps not light?



What will happen if an additional link is added as shown below?



CHAPTER 11

Electric currents

Currents in liquids, in gases, and in a vacuum; streams of electrons

With good practical experience of simple circuits and their behaviour behind us, we can turn to conduction itself; asking questions and doing experiments to provide answers to questions about a range of substances – liquids, gases and even a vacuum. The behaviour of an electron stream passing between two plates suggests that charges on the plates do push on the electrons in the beam; we can examine these forces with a brief set of experiments using static electric charges.

Running from the simplest circuit with a battery lighting a lamp to the first glimpse of a cathode ray oscilloscope, this series of experiments in Chapters 10 and 11 can contribute an enormous advance in knowledge. *We must give it time.* The outcome we hope to achieve is a cheerful sense of confidence with electric circuits rather than clearly organized, sophisticated knowledge that can be produced in an examination.

ELECTROLYSIS

We shall not treat electrolysis in great detail in this course, either now or in later years.

In schools that are also following the Nuffield Chemistry programme, pupils will study electrolysis fully in chemistry.

In other schools, it may seem unkind to do little justice to something so important as electrolysis. Yet it is probably better, in this physics programme, to spend only a short time on electrolysis and then in a following year repair any serious damage done by omission.

Before starting on electrolysis, the teacher should consult his colleagues in chemistry very carefully to find out what the pupils have already done or are likely to do soon in chemistry. In the Nuffield Chemistry programme, pupils meet electrolysis in Year 1, seeing or doing some of the experiments suggested below. However, they are likely to find the electric circuit already set up for them; so our experiments may represent new work in connecting up an electrolysis circuit and making it go. If the teacher decides to keep some electrolysis experiments in his physics programme for that reason he should certainly hurry them.

CURRENTS IN LIQUIDS

90 Class Experiment

Trying to send current through liquids

APPARATUS *item no.*

16 Worcester circuit boards *52C*
16 250-cm^3 beakers *512/1*
16 d.c. ammeters (0–1 A) *79*

Each group needs:

3 U-2 cells *52B*
2 Lamps *52A*
2 Connectors with lamp holders *52D*
Spring connectors *52E*
2 Plug/croc leads *52I*
2 Croc/croc leads *52J*
1 Hardboard disc with holes *52R*
2 15-cm lengths bare copper wire *52N*

The following should also be readily available:

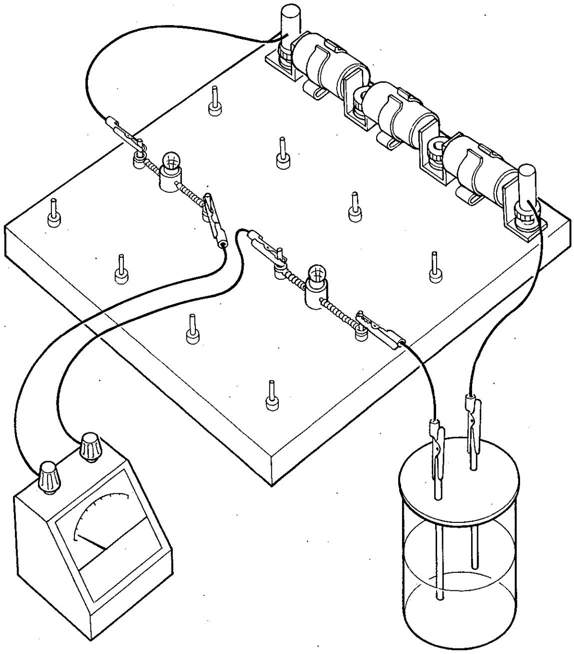
Distilled (or de-ionized) water
Copper sulphate crystals
Dilute sulphuric acid
Tap water
Salt
Sugar
Any oil

PROCEDURE

Pupils have tried to send electric currents through samples of various solid materials. We should now offer them liquids – obviously water to begin with. They can use a lamp or a meter to test for current. Run two wires from the gap where pupils have been inserting samples in a circuit into a beaker. Fill the beaker with distilled or de-ionized water. Then offer a little common salt or copper sulphate to be added to the water. Pupils should be asked to look and see what happens to each of the wires dipping into the water (electrodes), but this should not have too much emphasis now.

Then wash out the beaker and go back to distilled or de-ionized water and offer a little dilute sulphuric acid.

Start again (always washing the beaker) with tap water. Ask pupils what they see happening



with tap water and what they think that means. This is asking them to 'explain', to interpret some new observation in terms of older ones which seem more familiar. All they can say here is that they have seen that specially pure water does nothing and that adding salt or acid seems to make the water able to carry current, and since their tap water carries some current, it probably has things added to it. This is just a guess, but it is worth encouraging as a beginning of a scientist's treatment of things – explaining in terms of what else he has seen and knows rather than quoting an authority, such as a book, for an explanation.

Finally, start again and try distilled water with some added sugar and then some paraffin.

In all this we should *not* dictate formal conclusions; we should just let pupils see what happens and accumulate knowledge. But it would be sensible to let them develop their new skill in drawing circuits by recording the appropriate circuit diagram, adding arrows to show the 'official' direction in which 'positive' current flows.

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91 Class Experiment
Copper plating

APPARATUS *item no.*

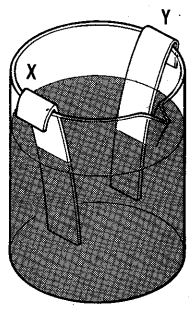
16 Worcester circuit boards *52C*
16 250-cm^3 beakers *512/1*
16 d.c. ammeters (0–1 A) *79*
Copper sulphate solution

Each group needs:
3 U-2 cells *52B*
2 Lamps *52A*
2 Connectors with lamp holders *52D*
Spring connectors *52E*
2 Plug/croc leads *52I*
2 Croc/croc leads *52J*
2 Strips copper foil *52T*
2 Carbon electrodes *52S*
1 Hardboard disc with holes *52R*
2 15-cm lengths bare copper wire *52N*

The copper foil is supplied in the Worcester circuit board kit in sheet. It should be cut into strips 5 mm wide and 1 cm longer than the depth of the beaker. One pair of these strips is needed for each circuit board.
The bare copper wire electrodes used in the previous experiment are not satisfactory for copper plating since the current density would be likely to be high with a consequent evolution of oxygen which would affect the current.

PROCEDURE

The two strips of copper foil are slipped down the inside wall of the beaker and the top centimetre bent back over the edge of the beaker. The crocodile clips of two connecting leads will then serve to keep the foils in place as well as make good electrical contact. The copper sulphate solution needs to be fairly strong (0.25 M).



The same circuit should be set up as in Experiment 90, but two lamps in the circuit will almost certainly be found preferable to one, in this experiment.

Pupils should use a solution of copper sulphate, being told that this is a chemical compound containing copper (and sulphur and oxygen). They should use small strips of thin copper for the two electrodes and let a current run for some minutes, and then look at the strips to see if they can see any difference. Then they should try the same thing using carbon pencil-leads as electrodes.

These leads will slip through the holes drilled in the beaker lids and can be kept in place with the crocodile clips of the two leads. That will suggest that copper is being deposited on one side and may raise the question of what happens on the other side. Then they should go back to the experiment with the little strips of copper.

Pupils should run the current for a minute or two, noting which electrode has fresh copper deposited on it, and then interchange the connections to the electrodes.

There will also be the question, 'Can we copper-plate other things?' The answer is, 'Go ahead and try'. (But we must be careful to avoid having objects of zinc or iron put into the bath to be plated, because those metals will displace the copper from solution and will confuse the story badly. Therefore, the teacher should censor the materials and try them himself beforehand. Nickel-plated iron will show this substitution.)

NOTE

This work of playing with electrolysis may seem childish, but if you let children try it, you will be suprised at the delight, and sense of knowledge, that it gives; and you will also be surprised at the time it takes. No one can tell before 'by guessing' how long a group of young people will take over this until they have tried it: but once they have tried it, they will be willing to give it the full time that it needs.

We shall not do any experiments with accurate weighing or embark on discussions of equivalent weights and Faraday's laws. Those will go to chemistry.

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92 Demonstration

The lead tree

APPARATUS *item no.*

1 L.T. variable voltage supply *59*
1 Cell to contain liquid *57B*
1 Projection lantern
Suitable electrodes
Solution of lead acetate
Connecting wire
A 12-V battery (item 176) can be used in place of the L.T. variable voltage supply.

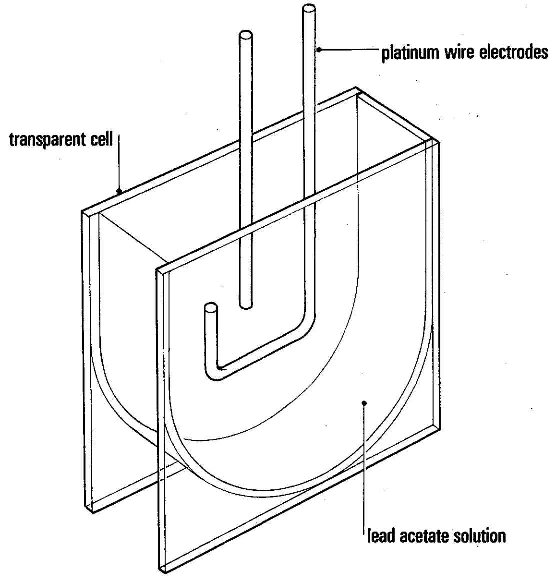
Notes on apparatus

The electrodes can be of carbon (for example, two pencil leads) but platinum wire is to be preferred.

A suitable strength is 30 g of lead acetate to 100 g of water. Should difficulty be expected in dissolving the lead acetate, add a few drops of glacial acetic acid.

PROCEDURE

Put the solution of lead acetate in the cell and arrange the two electrodes suitably. In the case of wire electrodes, one wire should run down one side and round the bottom as shown. The other wire, the central one, should be the cathode.



Place the cell in a projection lantern and pass a small current, preferably less than 50 mA. About 10 V d.c. may be necessary. A beautiful tree of crystalline lead will grow. It can be made to dwindle away by reversing the current.

Electric carriers: ions

With carbon rods, reversing the current will show that copper does leave one electrode ('the in-going wire' is a safer term for beginners), and that copper is plated on to the other (outgoing wire). We may suggest that some form of copper is travelling across; and also that the thing which we call electricity is also travelling across. And if it is travelling in that direction, coming from the positive knob of the battery, we may call it probably positive electricity. So we say in a discussion:

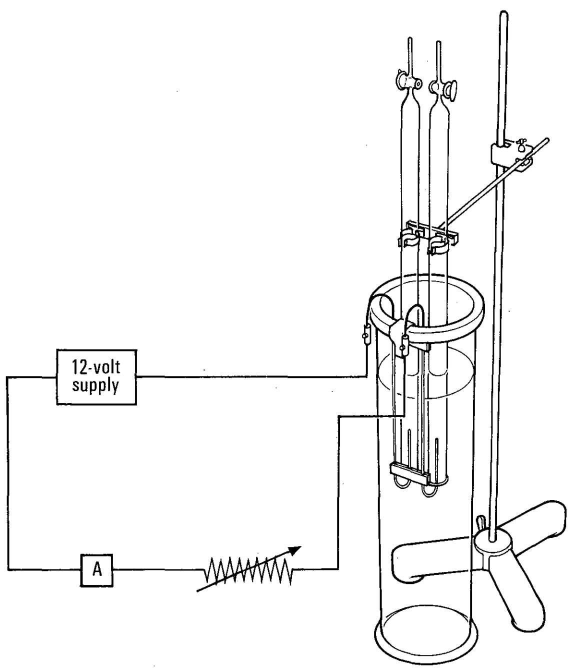
There may be some things made of copper, carrying electric charges across. Scientists believe that there are charged carriers; and they give them an old Greek name for travellers: 'ions'.

93 Demonstration
Ions in water

APPARATUS *item no.*

1 L.T. variable voltage supply *59*
1 Worcester gas voltameter kit *54*
1 Rheostat (10–15 Ω) *541*
1 Demonstration meter *70*
1 d.c. dial: 1 A *71/1*
1 Retort stand *503–504*
1 Boss *505*
Connecting wire
Sulphuric acid

The Hoffman type of voltameter is not considered suitable at this stage and the above voltameter is recommended.



PROCEDURE

Connect the voltameter into a series circuit of rheostat, ammeter and d.c. supply. Add a few drops of concentrated sulphuric acid and stir well before switching on. A current will now flow and the rheostat can be adjusted to give a suitable current of about 0.5 A. Bubbles will be seen at both electrodes and gas can be collected in the inverted burettes.

The relatively high solubility of oxygen in water makes it preferable to run the equipment for some time before the demonstration if acceptable volumes of oxygen are to be obtained.

If the current is too low, the inverted burettes should be raised a little.

Avoid plain copper wires, because the reactions at the electrodes then spoil our simple story: we see hydrogen emerging at one electrode, but there are no bubbles at the other. That is because the SO_4^{2-} ions arriving there attack the copper and form copper sulphate, which again forms ions. In fact, this is used as a way of separating radioactive copper from radioactive zinc in a piece of copper that has been bombarded with protons. As the electrolysis proceeds more and more copper ions join the solution and presently, instead of hydrogen being released at the other electrode, copper is deposited there.

Travelling ions The appearance of bubbles at both electrodes suggests that there may be ions travelling both ways. Explain clearly that this is only a guess, an imaginative suggestion, but one which other experiments, particularly in chemistry, support strongly. But do note that this tells us nothing at all about the way in which electricity is carried in copper and other metallic wires.

An investigation of electrolysis

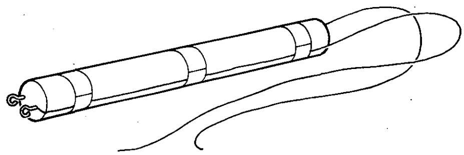
There are some very pretty experiments with electrolysis in wet blotting paper (or filter-paper or white cloth) containing indicators to show the products of electrolysis. They should be done very quickly. These involve too much chemical knowledge to be of use here to illustrate ideas of ions; but they do serve as indicators for electric currents. We shall find them useful with alternating current.

94 Class Experiment
The magic pen

APPARATUS *item no.*

4 Copper plates about 15 by 20 cm or similarly sized sheets of aluminium foil (kitchen foil)
4 Special styluses *57R*
4 12-V batteries *176*
4 Rheostats (10–15 Ω) *541*
4 Transformers *27*
Filter papers (large size)
Solution of potassium iodide (and starch)
Solution of potassium sulphate and phenolphthalein
Connecting wire

Special stylus
This is made from a 15 cm length of 15-mm dowel with two small screw eyes screwed into one end with a 60-cm, 26-SWG insulated copper lead secured to each end and taped to the dowel with Sellotape or rubber bands. They are supplied in the Year 2 general kit (item 57R).



PROCEDURE

If we break an electric circuit and carry the wires to a piece of paper soaked in potassium iodide solution, iodine will make a brown stain where its ions arrive. If we add phenolphthalein (dissolved in alcohol) to the solution, a crimson stain will appear where the potassium ions arrive. An easy method is to place the wet paper on a sheet of metal to act as a conducting back, and 'write' on it with a 'pen' consisting of two electrodes and connected to a battery. Draw this pen quickly across the wet paper. Ask pupils what will happen if the battery is reversed. Ask what they guess would happen if we connected it to an alternating supply. They do not yet know from their physics lessons what a.c. is; but they can guess what it is and they can guess at the answer to this question. It might be good to ask them to make a sketch in their notebook to show what they expect. Then provide an alternating supply of a few volts and let them try the experiment. (Make sure the transformer core is earthed.)

(Warning: some blotting papers contain bleaching agents, some paper contains starch. Either will alter the story. And some metals used for the backing sheet can spoil the effect).

This may seem to us little more than playing for fun; yet it seems to give young people a feeling of good sense about electric currents as well as entertainment.

The only danger in all this, at this early stage when it is only a matter of looking at things, is of electrolysis taking too long at the expense of many other important matters that lie ahead of us in this year.

Conductors and insulators We should point out that we have seen currents carried by metals, and some non-metals (e.g. carbon), and solutions (e.g. salt water), while some other liquids, such as oil or sugar solution, fail to conduct. Those substances which allow current to flow readily are called good conductors; those which do not allow current to flow are insulators.

CURRENTS IN GASES

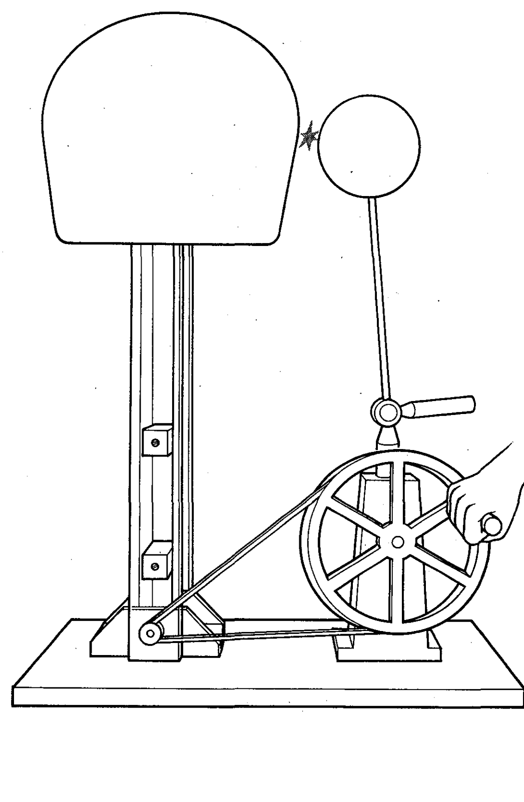
Can gases carry currents? Does the air carry currents? Suppose the air carried electric currents as easily as copper, what would happen to the electric circuits that you've been working with?... Then air cannot carry current at all easily or it would spoil your experiments. And what would happen to your batteries?... It looks as if air must be a non-conductor, a very good insulator like glass and paper and wood and cotton, and things like that. Yet we can persuade gases to carry currents. I will show you some experiments.

95 Demonstration
Making sparks *(Optional now)*

APPARATUS		*item no.*
1	Van de Graaff generator	*60/1*

PROCEDURE

The makers' instructions should be followed for the care and use of the Van de Graaff generator.



Make sparks with a Van de Graaff machine (or, lacking that, with a large insulated metal object charged up by repeated chargings from an electrophorus – the point is not to have a wonderful machine to make the sparks, but just to show that a spark can go through air). Show that when a spark jumps from some supply to an insulated object connected to earth through a microammeter there is then a current through the meter.

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96 Demonstration
Luminous gases

APPARATUS *item no.*

1 Van de Graaff generator *60/1*
1 Neon lamp
1 Fluorescent tube (optional)
2 Metal plates with insulating handles *65*
1 H.T. power supply *15*
1 Resistor (220 kΩ, 1 W)

A miniature neon lamp works satisfactorily and should be supplied with the accessories for the Van de Graaff generator.
When operated from the mains, such a lamp requires a safety resistor (usually 220 kΩ, 1 W) in series.

PROCEDURE

The neon lamp or the fluorescent tube is held near to the large sphere of the Van de Graaff generator, one contact being earthed through the hand.

The neon lamp should also be shown operating from the mains or from an H.T. power supply. Care needs to be taken with the connections in either case.

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97 Demonstration
Ions in the air

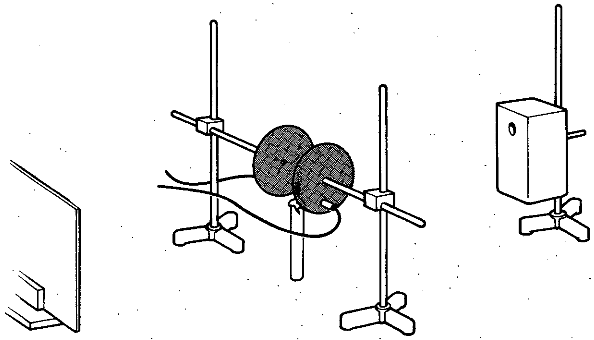
APPARATUS *item no.*

2 Metal plates with insulating handles *65*
1 E.H.T. power supply *14*
1 Compact light source *21*
1 Candle
1 Translucent screen *46/1*
1 L.T. variable voltage supply *59*

The Van de Graaff generator (item 60/1) can be used instead of the E.H.T. power supply.

PROCEDURE

Fix the plates in vertical planes parallel to each other and 5 to 10 cm apart by means of their handles held in retort stands and bosses. Light a candle flame and place it a little below the plates and roughly midway between them. Set up a compact light source about a metre away so that a shadow of the plates and the flame falls on a screen which is also about a metre away.



Apply a high potential to the plates from an E.H.T. power supply or from a Van de Graaff generator. The flame divides into two parts, one luminous, the other not; but both streams can be seen as shadows on the screen. The two streams will not look equal. There is no reason why they should do so, since one carries a stream of electrons, and the other carries a more complicated stream of ions.

These demonstrations are best done quickly at this stage. If the teacher has practised them beforehand and can run through them without much detailed explanation, they will make a good contribution here. We shall discuss currents in gases, and electron streams, more fully in Year 4.

CURRENTS IN A VACUUM

Then ask the final question: 'Can an electric current go through a vacuum?' Ask for comments and suggestions. Point out that the ordinary television tube has a vacuum inside. Pupils will say, 'Yes; but something must carry the current'.

Yes, a TV tube has a thing that releases electrons at one end and we arrange to drive those electrons down the tube so fast that they go slam into the face of the tube inside and make it glow. If there is a little gas left in the tube, by mistake, the electrons go slam into one gas molecule after another and make them glow. We can show that to you. (The glow does not show the crash of the electron hitting the air molecule. It comes just after that, when the molecule recovers from the damage of the collision – but that is something you will learn about much later.)

98a Demonstration
Observations with an electron beam

APPARATUS *item no.*

1 Double-(TEL 504) or fine-beam (Leybold) tube *61*
1 Stand *140 or 62*
(magnetic deflection coils are not used in this experiment)
1 H.T. power supply *15*
1 5-kΩ (20 W) resistor
4 12-V batteries *176*
(alternatively, the 0–25 V d.c. supply from item 15 may be used)
1 Potentiometer (15 Ω, 5 A) *541/1*
1 a.c. ammeter (0–1 A) *70 and 71/8*
1 d.c. ammeter (0–100 mA) *70 and 71/12*
1 d.c. voltmeter (0–50 V) } May be incorporated in
1 d.c. voltmeter (0–200 V) } the H.T. power supply (item 15)

PREPARATION *(TEL 504 double-beam tube)*

The tube is mounted in the stand so that the electron gun selection switch is uppermost. It is connected to the H.T. supply so that 0–300 V may be applied between the anode and the common cathode (lower socket of the tube cap). The heater (sockets on the tube cap) is connected to a 0–6.3 V a.c. or d.c. supply. It is advisable to monitor the heater current (0.3 A is normal) since the anode current is determined largely by the temperature of the cathode and it may be advantageous to adjust the heater voltage within the range 5–7 V.

The dual gun system of this tube provides two adjacent but independent guns, sharing the same anode voltage. Each gun carries a plate (D1, D2) which serves as one of the deflection plates for the other gun. The two other plates (D0) of the guns are supported between them and are connected electrically to a 4-mm plug mounted on the neck of the tube immediately opposite to the anode plug.

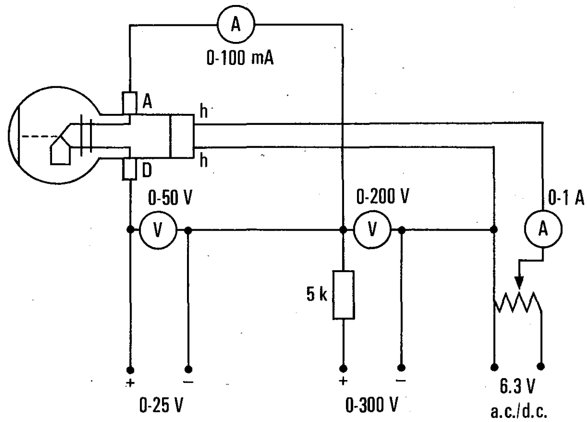
In this experiment the gun selector switch is thrown so that the horizontal electron beam appears. With all power supply potentiometers at zero, the gun voltage is raised from zero to provide about 0.3 A to the heater. Then the anode voltage is raised. At about 100 V, a short green beam should appear. As the voltage is increased carefully, this beam will lengthen and will strike the fluorescent screen. Anode currents typically range from 20 to 30 mA.

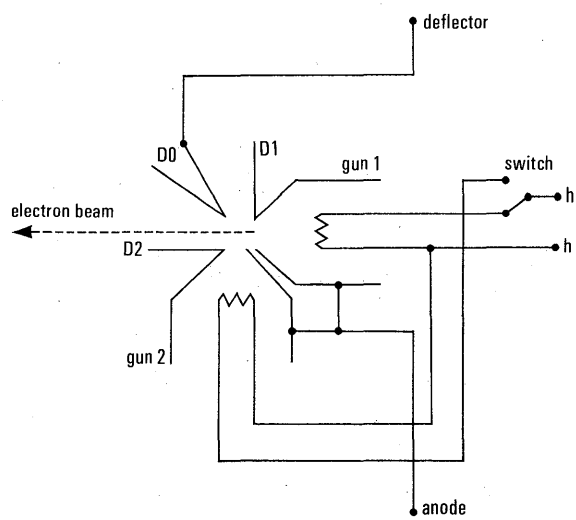
PROCEDURE

Let pupils gather round the tube, wait until their eyes are used to the half-dark, and then show them the electron gun with its orange-hot filament and say:

Now I will turn on the supply to drive the electrons out of the muzzle of the gun very fast. They'll shoot straight out in this direction.

Try a small gun voltage, then a bigger one, then a bigger one, until the children see the pencil of glow. Cut the gun voltage down a little, and





raise it a little, and let pupils watch what happens. Increase the gun voltage until the stream strikes the glass of the bulb.

NOTES

1. This experiment should be demonstrated to the pupils in groups of four to six in a well darkened room.
2. Always reduce the anode voltage to zero when not actually observing the beam.
3. The phosphor may suffer from charge build-up on its surface. Luminescence will not then occur until the beam is displaced (a permanent magnet may help this operation).
4. This tube contains helium at low pressure: and the beam emits predominantly green light.
5. The current-limiting 5-kΩ resistor must be used in the anode circuit as shown.
6. See below for a possible discussion with the class.

This big bulb has an 'electron gun' in it that releases electrons and drives them so that they come out from this small spout moving very fast indeed.‡ Then you can see the path they take because there is just a little gas – only a very little – left in this big globe, and that gas will glow when electrons hit it. (There is a pretty good vacuum in it, but a little gas has been let in.) So you can see the path of the electrons that come shooting out from this electron gun by looking for a little blue or greenish glow in the gas.

98b Demonstration
Swinging the electron beam

APPARATUS

As for Demonstration 98a.

PROCEDURE

With the beam forming a spot on the screen, apply an additional 0–20 V d.c. to the deflecting plate: note that the voltage applied to the plate can then be varied in the range (V_{anode}) to ($V_{anode}+25$ V) and observe the movement of the beam and of the spot. Reverse the connections to the deflecting plate and repeat.

If it is desired to apply an a.c. voltage to the plates, it is necessary to use a power pack output which is floating with respect to earth so that the a.c. voltage is superimposed upon the anode voltage.

See below for a possible discussion with the class.

We can pull the electrons in that stream over to one side by giving this little plate above the gun a positive charge, and that plate a negative charge, by connecting them to a battery here. Watch. Now reverse the battery. Now, add another battery. That looks rather like a man swinging a fire hose round to different directions.

What do you think would happen if we connected those two little plates to an alternating supply? Sometime you shall see that.

This is an experiment for real delight: for young people to 'see electrons' – though we must warn them that they are seeing them only indirectly – and enjoy the promise of understanding more atomic physics in the course of time. We should not labour the story with explanations about electric fields; though, of course, we can ask questions:

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‡*Note to teachers.* The final speed of electrons, that have been driven by a p.d. of 180 volts on the gun, is about 8 000 000 metres/second. In a TV tube with 7000 volts it is about 48 000 000 metres/second. It is best not to tell pupils any such values at this stage when we cannot support the statements.

What do you think is happening when the stream goes only so far in the very thin gas in the tube; and then, when we use a bigger driving push on the gun, the stream goes further? What do you think we're changing? Are we making a bigger electron, or a heavier one, or what?

For this first look, and for every look in later terms, it is important to have pupils near enough to the tube to see it properly. This is too important an experiment for a vague look from a distance. Only four or five pupils at a time are really able to see clearly. With adult physicists, one can gather a crowd of ten around the tube and still have them see; but beginners need and deserve a closer look. So the teachers should plan to have sufficient time for pupils to look in groups of four or five; and each of those groups needs several minutes for a good look at this unfamiliar sight.

(Some teachers report that their pupils see clearly from a considerable distance, so that the whole class can see the demonstration at once. Even so, we believe that this very important experiment deserves a much closer look than that.)

This is another experiment whose importance and demand for time are difficult to foresee until one has actually tried showing it with a complete class.

98c Demonstration
The cathode ray oscilloscope *(Optional now)*

APPARATUS *item no.*

As for Demonstration 98a together with:

1 Oscilloscope *64*
1 L.T. variable voltage supply *59*

PROCEDURE

If we turn the double-beam tube till its electron beam is horizontal, pointed straight out to the class, we have a model of a television tube. (In the latter, the deflection is done by magnetic fields, but it is best not to mention that now.) We also have tubes like this which are not used for television but do all kinds of jobs in science. This is called a cathode ray oscilloscope (C.R.O.). The teacher should turn the tube and show a C.R.O. beside it.

It is just a big tube with an electron gun at one end, and a very good vacuum inside (because we do not need to show the beam by glowing gas). It has a screen in front to show where the electrons hit. It has a pair of plates inside just like the little plates outside the gun in the big globe, and these can be given electric charges to pull the stream up and down so that the glowing spot on the front face can be moved up or down. There is another pair of plates also just beyond the gun, arranged to pull the electron stream sideways, so that we can swing the glowing spot to and fro sideways. So there are two pairs of plates, one pair like this‡ and one pair like this.‡ Here is the tube, and now we can start up the gun and make a green spot at the place where the electrons hit the front of the screen. If we connect this battery to this pair of plates, the spot moves across, like that. Then we can apply a battery to one pair of plates and another battery to the other pair of plates, so that we can move the beam across sideways and move it up or down, just as we like. In fact we can use this to plot graphs for us. You can see that the electrons obey orders and move the glowing spot to the new place far quicker than you can move any pencil when you're plotting a graph from point to point.

But we also have a very clever arrangement that will swing the spot smoothly across from left to right like this.

Then show the time base moving very slowly indeed.

Then we can use this to draw time graphs for us. The spot's up-and-down movement will show any electrical signal that we feed into it and plot that against time moving steadily along the horizontal axis. After each sweep across the bright spot is switched off (by an electronic trick), for the return journey – much as our own eyes and brain do when, reading, we move from one line to the beginning of the next.

Watch while the time base swings the spot across again and again and again. I will turn the battery on and off, on and off, to pull the electron-beam up and down, up and down.

Now let us stop the left to right movement and then connect this to the electric mains. We will use a transformer to transform down to a safe supply. Watch what happens. Why does the spot make a line like that? Has it moved up or down, or what?...

Yes, perhaps it is moving up and down very quickly, too quickly to see. Some of you may be able to see what is happening if you twist your head very quickly and watch out of the corner of your eye. But we can get at this much more easily by dragging the spot steadily across from left to right while this strange thing is going on. Then we shall be plotting a graph of what happens against time, from left to right like this: Monday, Tuesday, Wednesday, Thursday, Friday, ... not at that speed, but very fast indeed.

Let's turn off the supply and turn on the time base. There it is. Now turn on the supply. What does that pattern tell us about the supply? What will happen if our time base moves the spot across faster than that?... (Try that.) What would happen if we moved the time base much slower?

‡ For each pair of plates, the teacher holds his hands parallel, palms facing, either vertical or horizontal, to show the plate arrangement.

Double-beam tube with magnetic field: to be postponed The effect of a magnetic field is a marvellous sight, but it is much better to avoid this now and keep it for the next look at the tube. That raises more mysteries than it does good, at this stage – and it would be skimming cream from a later year's work.

Electric charges

We can ask a very important question about the oscilloscope and the 'double-beam tube': 'What is it that moves the electron stream sideways; what does the battery provide?'

Connecting those little plates just outside the gun to a battery puts what we call 'electric charges' on them which push and pull the electron stream and move it. I can put some electric charges on these two balloons just by rubbing them.

(This is a poor transition from the electric field in the oscilloscope to electrostatics experiments, because we do not use a battery on the balloons, and we do not get opposite charges on them. We should need much bigger voltages than are available. The highest voltage power-pack that is likely to be available will give 5000 V, and with that used to give opposite charges to two balloons – or to charge each balloon equally with respect to earth – the forces would be too small to be noticeable. For impressive forces we need a 20 000-V supply.)

99 Demonstration
Charges pushing and pulling

APPARATUS *item no.*

4 Balloons *57C*
1 Reel nylon thread *57K*

PROCEDURE

Hang up two inflated balloons by long nylon threads. The balloons must be far from any metal supports. Charge them with like charges. This is done by rubbing each balloon successively against one's jacket or pullover.

Having shown repulsion, take two more balloons and rub them together. It will be found that in practice this produces unlike charges on the two balloons, though often unequal in magnitude. With these oppositely charged balloons, show attraction.

ALTERNATIVE METHOD OF CHARGING BALLOONS

The balloons can be made to conduct by painting them with graphite, by spraying them with some aluminium sprays or by dipping them into a strong detergent solution which is allowed to dry.

Hang the two balloons up by insulating threads. Charge one of them. Bring the other balloon, uncharged, near to the charged balloon, but interpose a very thin sheet of plastic (such as polythene) between them. Touch the *un*charged balloon. Separate the balloons and they will be oppositely charged.

We can start pupils on class experiments with electrostatics by explaining that while *we* know quite a lot about electric charges and what they will do, and how the battery can bend the electron stream by putting charges on the plates, it is the pupils' turn to find out about those things for themselves.

100 Class Experiment
Electric charges

APPARATUS *item no.*

32 Conducting spheres *51D*
Reels of nylon *51E*
16 Cellulose acetate strips *51F*
16 Polythene strips *51G*
16 Wire stirrups for suspending strips *51H*
16 Retort stands, bosses, and clamps *503–506*

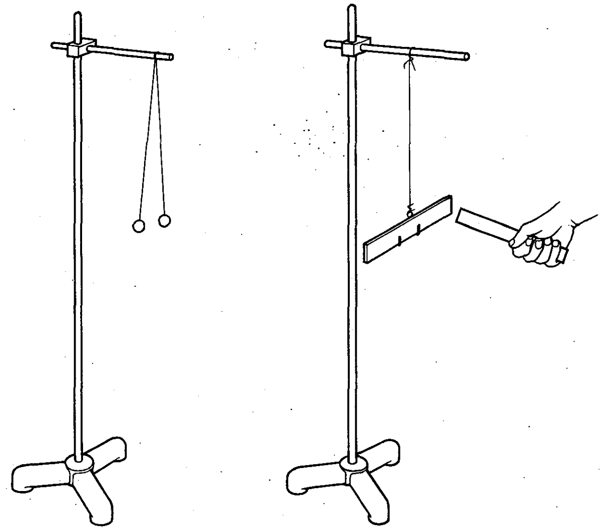
Materials to be tested as conductors or insulators, such as:
Nylon
Cotton
Wire
Paper (wet and dry).

The teacher should thread the plastic spheres with 45-cm lengths of nylon thread before the lesson begins using a needle or a light dab of adhesive.

PROCEDURE

The object of this experiment is for pupils to explore for themselves the properties of electric charges.

They can try rubbing the strips together and transferring charge from the strips to the conducting polystyrene spheres by wiping, using the edge of the strip. They can see the forces between charged spheres and charged strips. They can try the effect of touching a charged sphere with a variety of materials held in the fingers – some materials are suggested above.



They should draw simple sketches in their notebooks and record what they see happening.

Faster pupils might also try suspending, say, a polythene strip from a wire stirrup in order to look for forces of attraction and repulsion acting on it.

These class experiments are amusing and interesting, but we should make them go rather quickly. At this stage they will not yield a large body of well understood knowledge; and if we let them take much time we shall be tempted to clear up the story by definite teaching of further knowledge. That is better left until later; and anyway adding that would spoil the flavour of these 'open' experiments.

We expect pupils to find that when things are given 'charges' – whatever that may mean – they exert small forces upon each other; forces that are bigger when things are closer; and forces that are sometimes pulls, and sometimes pushes. (Give the words attraction and repulsion presently, but stick to the direct simple words at first.) They should find that there are two sorts of 'charge', and only two sorts. They should find that some materials seem to keep charges there very well – these we have called 'insulators'. Others seem to carry charges away, or if we try to give them charges, those charges run away, unless those things are supported on insulators. These latter we have called 'conductors'.

At this point, offer a clear statement of what 'charges' are. They are not, so far as we know at this stage, crowds of electrons, or remaindercrowds of atoms that have lost electrons – there is no evidence for those descriptions yet. We can say they are 'electricity', if we like, but that is only substituting one new word for another. To be honest, we must say that giving something a charge merely means doing something to it so that it pushes away other things that have been given the same kind of charge, picks up little bits of paper, and attracts things which have been given the other kind of charge.

Where have you met something like that before? Where have you met scientists describing something just by the things that it will do and saying, 'That is all we really know about it, in fact that is how we will have to measure it, by what it does'... Yes, we had to say that about electric currents, and now we have to say that about electric charges. So far as these experiments go, we don't know anything about them except that 'charge' means something extra that pushes or pulls.

101 Demonstration
A charging machine *(Optional)*

APPARATUS *item no.*

1 Van de Graaff generator *60/1*
1 Metallized polystyrene ball *51D*
Nylon filament *51E*
1 Set of accessories for the generator (optional) *60/2*

In the absence of a Van de Graaff generator, a good Wimshurst machine will do well.

PROCEDURE

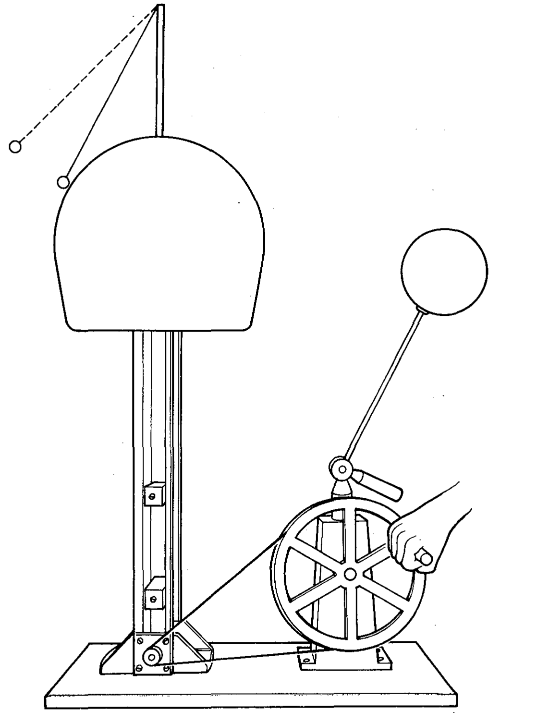
Show the machine at work. The discussion might follow on these lines:

We have a machine for doing the same kind of thing as this rubbing to make charges, almost like a charge factory. It was invented by a young man called Van de Graaff. There is now a company for making huge machines of this kind, some of them even 30 metres or more high. Here is our small Van de Graaff machine. That can pump up a huge charge on the big ball at the top. If we let it go on pumping, the charge on the big ball may be so great that it damages the air around it and sparks carry the charge away. We can let the big ball give some of its charge to a light metallized ball hung on an insulating thread.

We bring the small ball up to the big one on the machine and let it touch the big ball so that some charge runs on to it. Or we can let the big ball share some charge with a whole lot of bits of paper or light metal balls.

Now watch what happens if we try to let the big ball share its charge with the great Earth itself, by means of this wire.

One end of the wire may be connected to the discharging sphere of the generator; the other end to an earth connection – a water pipe perhaps, but not the casing of the electric mains.



That is another thing which we can say an electric charge will do: if we give things a big enough charge we can make sparks. We can call that another part of the description of what we mean by electric charge.

102 Demonstration
Comparing the motion of charges with currents

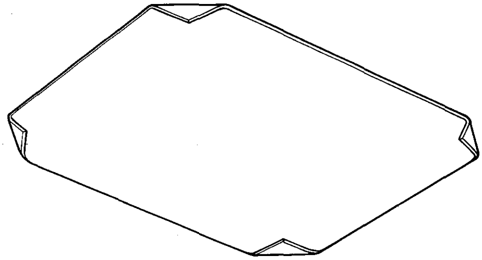
APPARATUS *item no.*

1 Van de Graaff generator *60/1*
2 Metal plates with insulating handles *65*
1 Table-tennis ball, coated with Aquadag *57L*
1 Reel nylon filament *51E*
1 E.H.T. power pack *14*
3 Retort stands, bosses, and clamps *503–506*

PROCEDURE

By fixing the handles in bosses, the two plates are set up parallel to each other with their planes vertical. They should be 8–12 cm apart. One of the plates is connected to the generator, the other is earthed, as is the lower end of the Van de Graaff machine. The plates recommended have a small peg at the back to which a crocodile clip or 4-mm socket can be attached.

Alternatively, a pair of metal plates, bent as shown, may be held upright in slotted bases and insulated by standing on polythene tiles or film.



The table-tennis ball, coated with Aquadag, is hung from a suitable length of nylon thread between the two plates. When the generator is switched on, the ball transfers charges between the plates. Previous trial will determine the optimum separation of the plates and the length of the thread.

We may say:

Instead of connecting the big ball to the earth direct, carry the wire from it as far as this metal plate, then have a space in air and another plate connected to the ground. If we hang a light ball by a long insulating thread, like a pendulum, between these two plates, it can collect some charge and move across and... Now watch it.

Then change from the Van de Graaff machine to a power pack. First earth all the equipment and then connect the positive terminal of the E.H.T. power pack (with the 50-megohm current-limiting resistor in circuit) to the first plate and repeat the experiment. If available, connect a sensitive galvanometer between the second plate and the connection to earth. The current may be explained by pointing out that the ball is carrying positive charge across one way and negative charge across the other way. Now that we have a power pack with terminals labelled positive and negative driving this 'current' of charges, we can talk more confidently about labelling the two kinds of charges 'positive' and 'negative'. (The galvanometer for this must be a sensitive one – with as high a current-sensitivity as possible for this use, although one should usually select the highest voltage-sensitivity in buying a galvanometer for many sensitive measurements. An internal light-beam instrument is a very useful luxury but smaller, cheaper galvanometers are available. For the present use, the shorter the period the better.)

Note on electrons moving At this point, some pupils may bring up the question of which moves, the positive charges moving one way or negative charges moving the opposite way, or both kinds moving in the two directions. We must be careful to be honest, and say that nothing in these experiments pupils are doing, or in most of the experiments that we ourselves know about, makes any distinction between these three possibilities. We simply do not know, from these experiments, which is right. Therefore, on strict principles, we should be wise to follow the general advice of physicists such as Einstein and Bohr, and not put unwarranted details into our descriptions. For that matter, Newton himself had some feeling in that direction when he wrote '*Hypotheses non fingo*' – 'I will not *feign* hypotheses' – though he also made many speculative guesses.

Children find it irritating if we say it is unwise to put in extra details. They want us to be 'really truthful'. So if we put our agnostic view to them, we should put it gently; and yet we should insist on keeping an open mind and we should always be wary about decorating our descriptions of the microscopic world with unnecessary details.

In that, we shall be following the practice of modern physicists, who make most progress in knowledge of atomic and nuclear structure by avoiding words and descriptions borrowed from the large-scale world. They try not to talk about the 'size' of an electron, because that may be meaningless in the microscopic world – it is certainly not a straightforward thing like the size of a billiard ball. They hesitate to say that a neutron 'contains' a proton and an electron in the way that we say an egg contains the yolk and the white. In general, we are warned that extending our vocabulary from the man-sized world to the microscopic world may lead us into paradoxes and mistakes.

Yet, here, pupils have heard of electrons and will themselves tell us it is electrons that move. So we should in practice move with the times – and accept this and say it, if pupils do not say it for us. But we must point out that while we believe that the moving things are only negative electrons in metals, there are positive things that move as well in semiconductors, and certainly both positive and negative moving ions in solutions and in gases. Our experiment with the table-tennis ball was a model of + and − ions moving opposite ways.

'When we make charges by "friction", one material pulls a few electrons off the other, leaving the latter positively charged.' Such descriptions are helpful, and children welcome them; but we should be careful not to sound too dogmatic. (See 'Note on teaching electrostatics with electrons' in the *General Introduction*, p. 52.)

Knowledge of charges and currents Children should have found some things about the behaviour of charges in their own class experiments; and we shall have shown in demonstrations some connection between the things that drive electric currents (batteries or power packs) and those electric charges.

Postpone electroscopes At this stage a gold leaf electroscope would not be particularly helpful and would take too much time. A little acquaintance with charges and forces is enough now, and we shall return to electrostatics in later years.

CHAPTER 12
More about forces
The pull of the Earth; the force of friction; force and pressure

This should be a short review of forces, with newtons used for measurement and weight described as 'the pull of the Earth'. It might even include a first look at the idea of gravitational field strength measured in newtons per kilogram. Throughout much of this we should try to use 'mass' in the proper places without much comment on it. We insist that *weight* is a *force* (with the peculiarities that it is 'vertical and unavoidable'). We suggest that *mass*, unlike weight, is a stodginess of stuff that stays the same everywhere. We shall look at motion, force and mass informally in later years; so there is no need for more than glimpses now.

The effect of adjustable fluid friction in bringing a falling object to a terminal speed should be explored, in preparation for Newton's laws in later years. (To children, as to adult Greeks, constant speed is the *natural* result of a steady force; and we need to face this before we can say that Newton's first law tells the true story.)

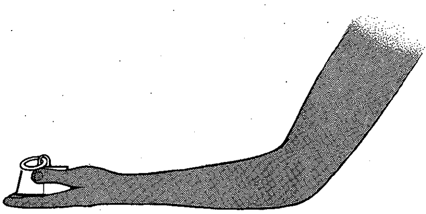
PULLS, PUSHES, AND MUSCLES

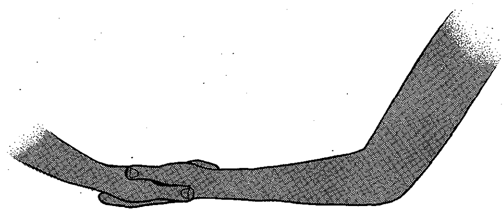
Our muscles which enable us to exert forces tell us something about the size of those forces.

103a Class Experiment
Muscle forces

APPARATUS *item no.*
16 1-kg masses *32*

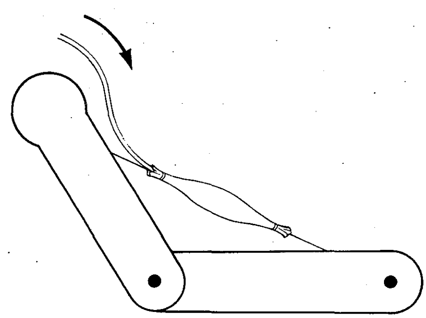
PROCEDURE
Ask each pupil to hold a load of a kilogram in his hand with his forearm out horizontally and feel his biceps muscle, also its tendons, as he raises the load. Then try the same without the load but with another child pushing down on that hand. This is just to emphasize our intuitive muscular sense of force.





103b Demonstration
A model arm

A working model to imitate a muscle is well worth the trouble of making. Make two pieces of plywood to represent an upper arm bone and a forearm bone, jointed at the elbow. Fix the top of the upper arm to a retort stand, allowing it to hang vertically. Then arrange a 'muscle' to pull the forearm up to a horizontal position.



The 'muscle' is a piece (about 20 cm) of bicycle inner tube tied tightly with string or wire to close it near each end. A rubber tube connected to a bicycle pump enters through the lower tie, so that this 'muscle' can be inflated – which will make it contract. Pieces of cord, representing tendons, run from the upper and lower ties to appropriate places on the upper arm and forearm. When the muscle is inflated it contracts and pulls the forearm up. If the ties are slightly leaky the model imitates a characteristic of real muscles – the pumping has to be repeated to maintain tension.

The Earth's pull

The Earth pulls every object towards it. Do other objects pull on each other? That is not a question to leave unanswered because pupils easily develop, and keep, the idea that weight is a peculiarity of the Earth alone. We should say that scientists do believe that every object attracts every other object, but that the attractions are very small indeed unless one of the objects is an immensely big massive one.

The Earth is so big that it pulls ordinary small things like this brick with enormous forces. Watch what that pull of the Earth, the weight of this brick, makes it do when I let it go. It moves faster and faster and faster, so much that it arrives with a crash on the ground like that.

Note: safeguarding ideas of mass and weight
All through this year, and right on through Years 3, 4, and 5, we should say again and again, whenever '*weight*' arises or is used in any discussion, '*the pull of the Earth*'. This will help to avoid some of the confusion between mass and weight which is promoted by the unfortunate variety of uses of 'weight' and 'weigh' both in common practice and in science. Try it, and you will find that this change to 'the pull of the Earth' will work magic.‡

Spring balances

A spring balance supported from a stand could just as well support the kilogram load – the spring stretching until it pulled upwards just as strongly as the Earth pulled downwards. The bigger the load hung on the balance, the more the spring stretches. Springs used to measure forces in this way are usually calibrated in newtons (and a newton is almost exactly one-tenth of the pull of the Earth on 1 kg).

‡ In a later year we shall talk of the Earth's gravitational field; and we shall make the Earth's gravitational field strength an important concept in calculating weights. g is the acceleration of a freely falling body; but it is also the strength of the Earth's gravitational field. A freely falling body has an acceleration of 9.8 metres per second per second; but a body at rest (or with any kind of motion) is pulled by the Earth with a strength of 9.8 newtons per kilogram. It would be absurd for anyone (except a General Relativity expert) to say that an object at rest has an acceleration of 9.8 metres per second per second; but it is quite sensible to say that such an object is pulled with an Earth-pull of 9.8 newtons on each kilogram of stuff in it. Adopting the latter view will make it easier in Year 4 to handle absolute units for forces in calculations.

104 Class Experiment
Marking a spring balance for use

APPARATUS *item no.*
16 Spring balances *43*
16 Weight hangers with slotted weights (100 g) *31/2*
16 Unknown masses of about 750 g
'Write on' Sellotape *571*

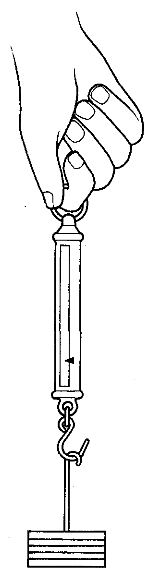
The spring balances need to be blank and this can conveniently be arranged by covering the scale of the calibrated spring balances with 'write on' Sellotape strip.

PROCEDURE

The teacher may say:

Here is a blank spring balance with a good spring but no marks on it, no scale. I will give each of you one of these balances and some chunks of metal, all alike, that are 100 grams each, a tenth of a kilogram.

Hang a chunk on your balance and make a mark at the place where the pointer is. If you work with a partner, make sure you both agree where the mark should be. Then try another of the lumps to see whether it is just the same as the first one. If it is not, please complain to me. Now hang both lumps on the balance and make another mark labelled '2'. Why did you have to make sure that the second chunk pulled the spring to the same place as the first chunk before this? Then mark 3 and 4 and so on, as far as you can go.



We certainly should not raise any question with children about the assumption behind this calibration process, yet the teacher should keep it in mind: we assume that four equal lumps hung together on a spring pull it down with four times as big a force as one lump. We have to make some assumption like this in constructing a scale of measurement for a thing like force. There are other systems of defining and measuring force, but the equivalent assumption will always be there, though it is sometimes more deeply concealed. In our teaching, we should take this assumption as obvious and necessary. It is not really a weakness in our construction of physics; but rather a definition of how we are trying to construct physics to express our understanding of Nature. Yet there is some knowledge of Nature in our statement that the Earth pulls four equal lumps together with just four times its pull on one lump; this agrees with the experimental fact that gravitational pulls do not interact with each other, but simply add up – the Earth's pull on the upper lump is not shielded by the presence of the lumps underneath it.

When children have made calibrated spring balances, we may give them an object such as a lump of rock to weigh on their balance, saying; 'Find out how much the Earth pulls on this piece of rock, in whatever units you have used for making your balance.'

This simple experiment, which may seem almost pointless to us, is an important example for beginners to show how scales of measurement are made, and perhaps to reinforce the idea of weight as the pull of the Earth by doing something with it.

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105 Demonstration

Weighing

(= finding the pull of the Earth on) a brick

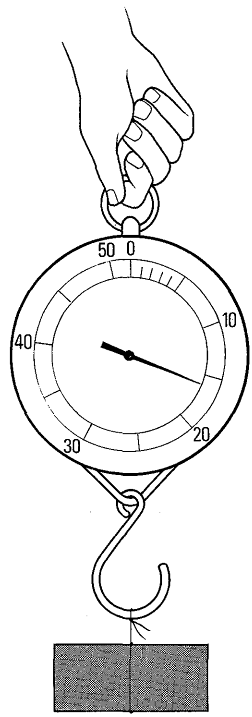
APPARATUS *item no.*

1 Demonstration spring balance (50 N) *85*
1 1-kg load *32*
1 Brick

PROCEDURE

The teacher may say:

We measure the pull of the Earth on things in several ways. We can measure it by letting it pull out a spring, as in this spring balance. If I want to know the pull of the Earth on this brick, I hang it on a spring balance and it stretches the spring until the spring pulls the brick up with its own tension forces just as strongly as the Earth pulls the brick down. Then I read the balance.



Hooke's law and spring balances We did not appeal to Hooke's law in calibrating the balance. As we have used it here, the spring need not obey Hooke's law as long as it is 'elastic', that is, as long as it does not become permanently distorted. Manufacturers of spring balances are glad of the fact that such springs give an even spacing of marks on their scale. That is a 'linear scale'. But here we do not need Hooke's law, because we can make our marks on a balance anyway.

106 Class Experiment

A feeling for weight: the forces box

APPARATUS *item no.*

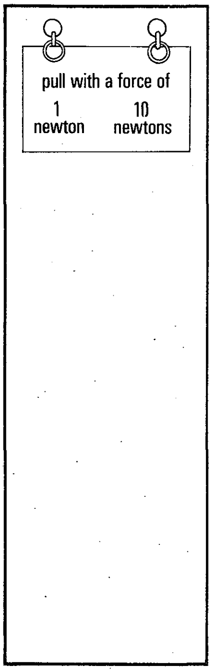
1 Forces demonstration box *63*

Details of the demonstration box

This box is made from a framework about 1.2 m high, 30 cm wide and 10 cm deep, with a projecting wooden bar at the back, which can be G-clamped to a laboratory bench. Two freely running pulleys are mounted near the top of the framework. Strings running over these pulleys link two metal rings (outside) to masses of 1 kg and 102 g (inside). These masses can move vertically through a distance of 1 m. The front of the box is closed with hardboard and carries the legends 'pull with a force of 10 N', 'pull with a force of 1 N'. The back of the box is open so that the mechanism can be seen.

PROCEDURE

The box should be clamped firmly to a bench and left available for pupils to feel the forces required to lift the hidden masses. These are forces of 1 N and about 10 N. Leaving the box available for some time ensures that the pupils can reinforce their knowledge and also avoids a queue.



NOTE

The positions of the masses in the box should be arranged so that the strings can travel through 1 m. This means that pulling the strings to the full extent will transform 1 J and 10 J respectively. This will be used in Year 4 of the programme.

We might say:

You will find a string coming out of that box over there which will let you feel 1 newton of force. And another string pulls with 10 newtons of force. Go round to the back of the box and you'll see how it's all arranged. We'll keep the box there for some time so that you can feel what those forces are like.

---

107 Class Experiment

A feeling for mass

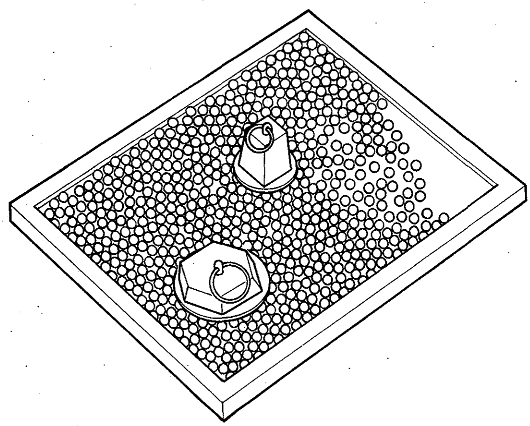
APPARATUS *item no.*

1 Mounted glass plate *86*
1 1-kg mass *32*
Steel ball-bearing balls
(about 1.5 mm diameter) *57P*

The polystyrene beads can be used in place of the ball-bearing balls.

PROCEDURE

The 1-kg mass with a smooth base rests on the layer of ball-bearing balls which are spread thinly over the glass plate. This reduces friction to small proportions. The mass can then be pushed from side to side to get the feel of getting a mass of one kilogram moving.



As with certain other experiments throughout the year, this tray should be left at the side of the laboratory for pupils to try on their own in order to increase their acquaintance with the concept of inertia.

A 0.5-kg mass should also be put on the glass plate so that the pupils can get the feel of that.

We can say:

If you'd like to feel what a kilogram of *stuff* feels like without bothering to lift its weight – pull against the Earth's pull on it – you can just shove a kilogram along on the flat coasting-table over there. The tiny balls are there to act as rollers and make the friction almost nothing. Then you can feel what it costs you to get that kilogram of stuff moving without having to push hard against any friction. Even if there is no friction, you still have to push hard if you want to get a thing moving very fast; or else you have to go on pushing for a long time. That is a really important thing about all kinds of matter: to get it moving or make it move faster you have to push it.

FRICTION

As another study of forces, give a quick demonstration on friction or encourage a class experiment to be done quickly. This is to provide familiarity. Any attempt to extract 'laws' – or worse still to give laws and ask pupils to verify them – would be a mistake here.

108a Demonstration
Investigating friction

APPARATUS *item no.*

1 Friction kit: *55*
1 Smooth plank with screw eye (about 75 × 15 × 2 cm) *55A*
1 Smooth block with screw eye (about 25 × 12 × 2 cm) *55B*
3 Extra blocks without screw eye (about 25 × 12 × 2 cm) *55C*
10 Rollers of 12-mm stainless steel (smooth-ground) rod, 20 cm long *55D*
1 Crank assembly *55E*
1 Demonstration spring balance (50 N) *85*

PROCEDURE

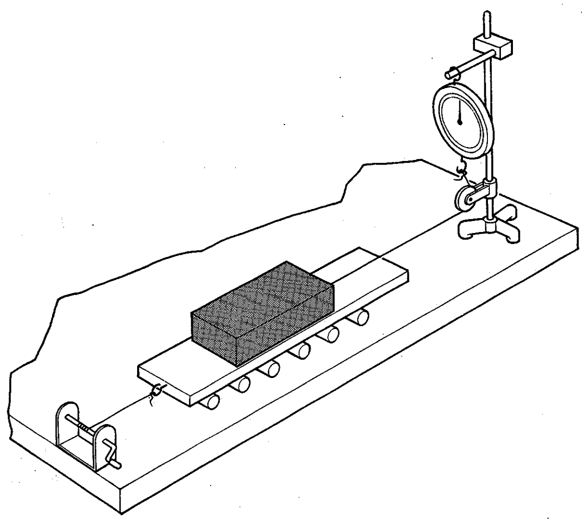
Drag a block along a plank with a spring balance and look at the force. Press the block against the plank with a finger to increase the force pushing block against plank, and again drag the block along with the spring balance.

If the friction force does not show clearly on the spring balance, change to another of lower range, for example the 10-N spring balance (item 43).

108b Demonstration
Friction with smoother motion

PROCEDURE

It is difficult for pupils or for a teacher giving demonstrations to make consistent measurements, because the spring balance jiggles while it is being carried along and gives uneven readings. It is not so much the friction that is uneven as the motion of the operator's hand. To avoid that trouble, place the plank on rollers and pull the plank along at constant speed by a string which is being wound by hand on a crank. Meanwhile hold the block at rest (while the plank moves along under it), by a horizontal string from the block to a spring balance held at rest. That will give steadier reading. If this is done as a class experiment, ask definite questions and urge the class to look for answers roughly and quickly.



Press the block down against the plank with a finger and again drag the plank along. The spring balance will now show a greater force.

Add an equal block on top of the first so that the force pushing the block on to the plank is doubled. Measure the frictional force. Increase the load with two, three, or four blocks and see how the frictional force increases.

We may say:

Once the board is moving along smoothly under the block, does the friction force stay the same, or does it change a great deal from one run to the next? If it does, we must take two or three runs and average them.

Let us pile a load on top of the block to press the block against the board with a bigger force than just the weight of the block itself. I will tell you the weight of the block, or you can go and find it with the balance. Put an equal load on top of it; when we have two blocks' worth pressing the block down on to the tables we have doubled the force pressing them together. Try the friction again. Try the friction with three times the force pressing them together.

If you have time, go back to the plain block and try friction for different speeds.

I must warn you that what really happens in all these things has been investigated with microscopes and other things that look into tiny details in the surfaces, and the full story has been found to be much more complicated. This is only a rough look at the general behaviour.

Friction is an adjustable fellow, up to a point. We will leave the plank at rest and just put the block loosely on the plank. You'll see that the spring balance reads 0. Now let us gently wind the plank along without letting the block start slipping. The block will be carried along a little way with the plank as it stretches the spring balance. Look at the force; then more force; and then still more force, until the block starts slipping. We will try that several times because it tells something worth knowing about friction. You may see something that is important to people who drive cars and want to avoid skidding.

All this should be done very quickly – it deserves one period at most, not two.

FLUID FRICTION

Fluid friction is interesting and forms a valuable beginning for Newton's laws of motion. Instead of announcing Newton's laws as the right rules, as one might do in discussing things with a mature scientist, we shall be wiser to start looking at motion with friction, which is more common in the real world. Solid friction does not give such an interesting story as fluid friction, which has the important property of increasing its force with increasing speed. So a body whose motion is controlled by fluid friction will, if pulled by constant force, approach a constant speed (terminal velocity). This is what happens with parachutes, raindrops, clouds, divers in water. It is even what really happens with many an object thrown out of an aeroplane as in a physics problem and allowed to fall through a large distance. Such problems often ask for results calculated from acceleration formulae for free fall when in fact, with the distances given, the object would be approaching terminal velocity.

Discussion of fluid friction When we teach anything about fluid friction, or when we encourage pupils to try class experiments on it, we must bear in mind at least two different types of fluid friction: the kind associated with very slow streamline motion (as for Stokes's law), and the kind that leaves a wake of vortex motion and has a resistance that varies as the square of the speed.

Experts in fluid dynamics warn us that both our commonsense thinking as physicists and most textbooks are misleading about fluid friction. When we increase the speed the whole pattern of flow round the moving object may change, and if so the 'constant' in the formula for friction will change. And at even higher speeds the whole relationship may change completely, as mentioned above. So the simple laws that are often quoted do not apply well over a wide range of speed. What follows here is only a description of two simple, but rather extreme, cases of motion through real fluids. Incidentally, the experts agree that if we could try moving an object through an *ideal* fluid with no viscosity, we should find that it experienced no resistance or drag at all.

For very slow motion through a viscous fluid, friction varies as speed, and (for a given shape) as the first power of a linear dimension such as the radius of a sphere: $F = krv$. In air, ordinary raindrops fall far too fast for this to apply. It does hold for the tiniest drops in fog or clouds.

For much faster motion we may regard the resistance as due to the body leaving behind it a wake of fluid in confused motion with kinetic energy; and then the resistance varies as v^2 and varies as the density of fluid (d), varies as (linear dimensions)^2 and does not involve the viscosity coefficient: $F = k'dr^2v^2$.

We certainly should not tell pupils any of this detailed story; but we may find it useful ourselves in interpreting what happens.

109a Class Experiment
Falling through water

APPARATUS *item no.*

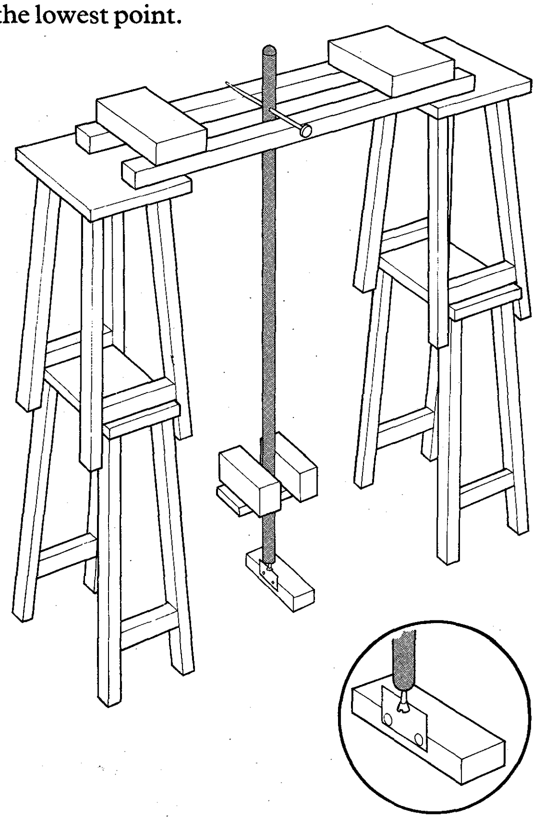
16 Gas jars *514*
16 Chinagraph pencils or felt-tip pens *543*
1 Heavy pendulum *10F*
Styrocell beads *57E*

The heavy pendulum suggested is the 'broomstick' pendulum of Year 1. This ticks seconds (see Experiment 28b).
Each pair of students will need from 30 to 50 styrocell beads, which are the raw material from which expanded polystyrene is made and whose density is slightly greater than that of water.

PROCEDURE

Give pupils a tall glass jar of water – a gas jar perhaps – with some small beads which will fall slowly through water (e.g. styrocell beads, pieces of wood or wax weighted with wire, scraps of solid plastic or of chalk). Ask them to find out what they can about the falling motion.

Pupils will ask for a clock; but a stopwatch or even an ordinary clock will prolong this quick look at fluid friction unduly; so we should just provide some device that ticks loudly about once a second. If possible, use the large crude pendulum suggested for Year 1: a broomstick loaded with two bricks swinging on a nail. A projecting spike at the bottom of the broomstick hits a card each time it passes through the lowest point. The clicks made by that are clearly audible and pupils can use them for timing distances. The card should be arranged so that it is at right angles to the plane of swing of the pendulum, so that the spike gives it a sharp tap. The bigger the area of the card the better. If instead of holding it in a clamp at the bottom, we bend a portion of the lower edge at right angles and strap it to a sheet of paper or rubber across a large beaker, we shall get even more sound from it. Or the spike can be arranged to hit a bell like the gong of an electric bell. If the background noise in the classroom is so great that even these signals are not audible, then the teacher, or a pupil, may make loud taps or hand-claps instead each time the pendulum swings through the lowest point.



When the pendulum hits the card it loses some energy, so the amplitude will die down. But the time of swing of the pendulum is almost independent of its amplitude; so it will keep good time. The card delivers an opposing impulse to the pendulum at the mid-point of its swing, and that does not change the phase of the motion, so no part of a cycle is gained or lost at that impact, and therefore the timing is good. If the teacher likes, he can even keep the pendulum going by giving it an occasional impulse with his hand, always at the mid-point of the swing.

We offer a felt-tip pen or special pencil to mark the stages of fall on the jar. The behaviour of 'styrocell' beads is interesting for they will fall at various terminal velocities in water. Pupils should find that the motion quickly approaches an almost constant speed. If not, it is because the bead is too dense and therefore needs a longer distance of fall before it is close to its (greater) terminal velocity. In that case, we should substitute heavy oil and let pupils crowd round and watch it. We should *not* give any discussion of gravity fall at this stage – that would make the motion of the bead seem *unnatural*! But we may ask naïvely, 'Why doesn't it move faster and faster?'

NOTE

A drop of detergent in the water will help to prevent the beads from clinging to the surface.

Air resistance

109b Class Experiment
'Slow-motion raindrops'

The styrocell beads may be made to swell to many times their original size by boiling them in water for five minutes or so. If these *expanded* beads are allowed to fall freely in air, they will approach a terminal velocity in falling about a quarter of a metre. They behave like 'slow-motion raindrops'.

NOTE

Unexpanded beads should be stored in a cool place, preferably in a sealed container. Expanded beads should not be stored.

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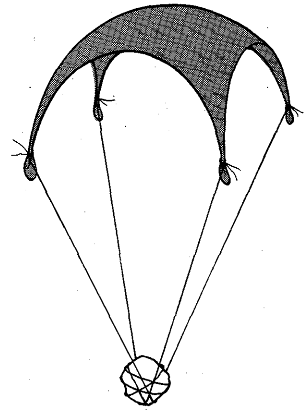
110 Home Experiment
Parachute and wing models

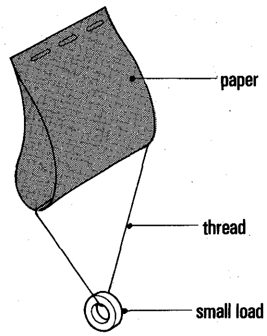
APPARATUS *item no.*

1 Table-tennis ball *57M*
1 Improvised paper or cloth parachute



PROCEDURE

The ball is dropped first by itself and then with the simple parachute attached. A handkerchief is suitable for this – the ball being attached with the help of Sellotape and thread.

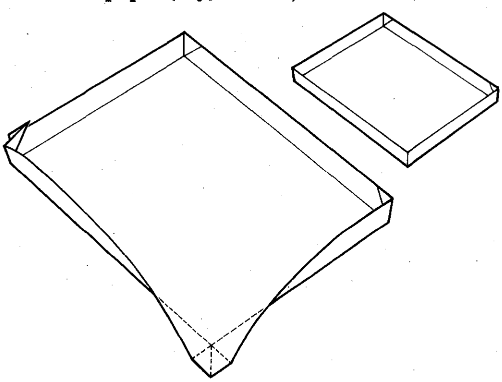


A piece of paper can be made into a model of an aircraft wing as shown.

111a Class Experiment
Air resistance

APPARATUS

Sheets of paper (say, A5 size)



PROCEDURE

Show pupils how to streamline a sheet of paper by bending up the edges to make a little rectangular tea-tray. On a 20 cm × 15 cm sheet of paper, the bent-up sides should be about 2 cm high, and smaller trays should have sides in about the same proportion. Point out that a plain sheet of paper flutters when allowed to fall, but the tray falls more steadily. Ask pupils to find out all they can about the way such a tray falls. Tell them they have 20 minutes to find as much as they can and that, after that, when we hold a council-of-war to find out who has discovered what, they'll be sorry if they haven't managed to try quite a number of different things. Then give them more than 20 minutes – because, when young people start trying things they take some time to get going. It would be a great pity to give detailed instructions and simply have pupils observe what they're told to look for.

With some groups, this play with paper trays can be very interesting and fruitful. It strikes other groups as childish, and as an opportunity for undisciplined waste of time. In the latter case, we should either avoid the experiment or give it limited time near the end of a class period; and perhaps preface it with the following two demonstrations which give a hint of a serious use of experiments with paper in future years:

1. Hold two sheets of thin paper vertically and parallel, about 2 cm apart. Hold your mouth just above the sheets at the top and blow a strong current of breath down through the space between the sheets. Before doing it ask what the pupils expect will happen. Then either do the experiment yourself or let pupils try it.
2. Hold a sheet of paper by one edge, pulling that edge taut, horizontal, by holding the two corners with finger and thumb of two hands. Bring that edge up just under your lower lip so that the rest of the sheet projects away from your face, curving down under gravity. Ask what will happen when you blow a strong current of breath over the top of the sheet. The previous experiment may offer a hint. Try it, or let pupils try it; and then point out that this may show the secret of the way in which the air supports an aeroplane.

With the paper trays there are several different things to find (but we should not suggest these): the effect of starting the tray upside-down; the effect of starting it near the ground or high above; the behaviour of the air as the tray goes past (if someone has some smoke available); the effect of changing to a smaller tray of the same paper, and the effect of loading up the tray with multiple masses of the same paper to change the gravity force. We should not expect pupils to think of all these possible things to try, and still less should we expect them to provide clear answers. The last question of all, friction force vs terminal velocity, is too hard and should neither be asked nor answered at this point; but a physicist at a later stage can have a lot of fun with it and arrive at a very interesting, clear conclusion.

All we want from these experiments is just a feeling for the way in which fluid friction brings a moving body to a practically constant speed. If we could deal with friction in a single period – by some compression, some light-hearted skipping and some complete omissions – that would be better than spending three periods on it. At this point, we would like pupils to know about friction; but we want to hurry on to studies of work and energy.

Where the equipment is readily available, this discussion might end with a demonstration of small steel ball-bearing balls falling in a tall jar of glycerine or heavy liquid paraffin.

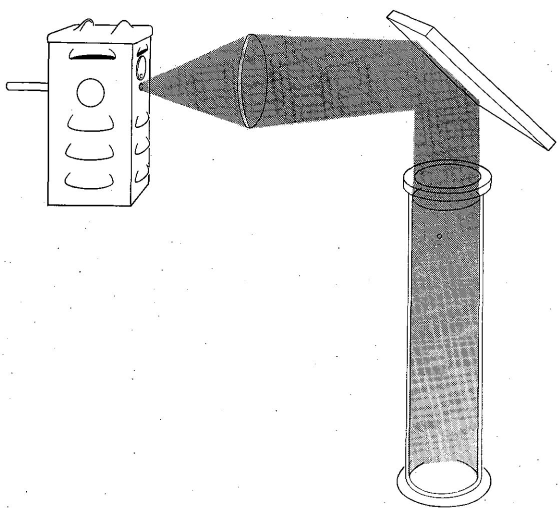
111b Demonstration
Fluid friction in a viscous medium *(Optional)*

APPARATUS *item no.*

1 1000-cm^3 measuring cylinder *518/2*
Glycerine or a viscous oil such as liquid paraffin
20 to 30 Steel ball-bearing balls (3 mm) *57N*
20 to 30 Steel ball-bearing balls (1.5 mm) *57P*
1 Chinagraph pencil or felt-tip pen *543*

PROCEDURE

The ball-bearings are allowed to fall freely through the liquid by gently releasing them just above the liquid surface.



The tube is marked off in four or more equal divisions of length by pencil marks, or by rubber bands. The timing is done by pupils listening to hand claps made as the ball passes each mark (rather than by a stop-clock, which would over-emphasize precision at the expense of the general picture).

The balls should be placed in a dish of the same liquid before use to reduce the danger of air bubbles.

NOTES

1. For best viewing, shine a strong beam of light down the tube from a compact source above the top. In a half-dark room, the balls will appear as tiny spots of light.
2. The balls can be retrieved with the aid of a magnet.
3. A tall glass tube if available is better than the measuring cylinder.

Force and pressure

That the atmosphere can exert a force large enough to collapse an empty can, or to support a column of mercury $\frac{3}{4}$ m tall has been demonstrated in Year 1 (see Experiments 45 and 46).

To find out just how large the force is we could weigh that column of mercury; if it had a cross-sectional area of 1 cm^2, its volume would be 75 cm^3 and its mass 75×13.6 g, just over 1 kg.

The pull of the Earth on a mass of 1 kg is 10 newtons. The atmosphere exerts that force on every square centimetre of the Earth's surface – that is 100 000 or 10^5 newtons per square metre. Some pressures:

	cm of mercury	newton per m^2	newton per cm^2	p.s.i.*
The atmosphere	76	10^5	10	15
A motor car tyre (above zero)	200	2.7×10^5	27	40
(above atmospheric pressure)	124	1.7×10^5	17	25
Blood pressure	80–120	$1.05–1.6 \times 10^5$	10.5–16	16–24

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‡ The p.s.i. is an old unit still in use for quoting tyre pressures. 10^5 newton per m^2 is also called one bar.

CHAPTER 13
Using energy
More about jobs and energy shifts; work; machines that multiply forces

The discussion of energy in this year should be fuller and more mature than in the first year. We should use [work] calculated as [force] × [distance] as the measured *transfer* of energy from one form to another form. (See Section VI of the *General Introduction*.)

We should carry children through many examples of energy changes in great variety. Although some changes can now be measured by work, this should still be a light-hearted tour to get further acquainted with the very important foreign country called Energy. It should be a holiday trip, crowded with exciting events.

In those many examples where a human being or an animal does a job we should continue to pay attention to the source, chemical energy from food.

We go back to the lever experiment and point out that it will give us a big force for a small one if we choose unequal distances. It is a 'force multiplier'. We ask if it will also 'multiply' energy for us. We look at the input force pushing down and the output load being raised and find we have no gain or loss. We at once say that this is an important thing about energy: 'You do not gain or lose'.

Fuel In Year 1, we introduced energy as something stored in fuel, something whose *move* from fuel can get useful jobs done. Even then, we did not say fuel produced the energy; we only said it 'released it'. We did not say we 'used' the energy – as if we consumed it – but we said the useful job is done as the energy is transferred from its stored form in fuel to some other form such as potential energy of a raised load or heat in bathwater.

Energy changes in doing useful jobs In teaching Year 2, we should remember that energy *changes* are often more important than energy itself. If we haul a load of bricks up to the top of a building using our own arms and a pulley system, we transfer a considerable amount of energy from an invisible store of chemical energy form in our body to gravitational potential energy, equally invisible, located somewhere in the gravitational field. The useful thing is that we have raised the bricks higher up. That was not done by any energy being manufactured or by any energy disappearing but only by some energy *changing* from one form to another. We have also moved the energy from one place to another, but while we are fairly sure that it resided in our body, when it was in chemical form, we can hardly tell quite where it is when it is in the form of potential energy, presumably in the gravitational field and therefore not very easy to locate.

Energy changes from . . . to . . . All through discussions of energy now and later, we should carefully name the two forms between which the transfer occurs. We should say, for example, 'So much energy is transferred FROM chemical form stored in our muscles TO motion energy'. It makes things easier and clearer if we underline FROM and TO, and insist on pupils always telling us the two forms and including FROM and TO in their statements.

Work We use work not as a form of energy itself but as a calculated number-statement, of the quantity of energy transferred from one form to another. Thus, if we have a 2-kg brick pulled by the Earth with a weight of 20 newtons and raise it 3 metres, we calculate the work to show how much energy is transferred. We state that in full 'the transfer of energy from chemical form to potential energy is 60 newton·metres'.

This unit is so useful that we give it a special name and call it 1 joule. (If pupils ask how we prove that a joule is a newton · metre, we explain that this is just a shorthand word for a newton · metre so there can be no proof. 'How would you *prove* a knot is a sea mile per hour? It just is a name for that.')

DISCUSSION OF ENERGY

In our present teaching of energy, which continues the building of acqaintance from Year 1, we shall use informal names for several forms of energy whose official names would be puzzling and add difficulties. These are:

'*Motion energy*' for *kinetic energy*. In our treatment below, we shall use this informal name when we are suggesting discussions with pupils. But we shall, of course, refer to it as kinetic energy or just K.E., when we are discussing policy or methods with teachers.

'*Uphill energy*' instead of *gravitational potential energy*. Again, we shall use this informal name in our suggestions for teaching, but we shall of course call it P.E. in our own discussions as physicists.

'*Springs energy*' instead of *strain energy* of a wound-up clock spring or a stretched wire, or a bent beam. This wording may sound uncouth, but we believe it will help in teaching at this stage, by conveying the feeling of springy material holding some stored-up energy. However, when strain energy is involved in some machinery which is transferring energy from, say steam in a cylinder to, say, spin energy of a fly-wheel, we shall evade some difficult distinctions by calling that '*mechanical energy*'. (In fact, when ropes, pistons, levers, etc., transfer energy from one place to another or transform it from one kind to another, the energy does go through some form which we should call strain energy, essentially travelling in some form of waves. This raises considerable difficulties, even to ourselves, both in picturing the location and behaviour of that energy and in explaining its transport. Therefore this part of any discussion of energy transfer should be avoided in elementary teaching.)

'*Light energy*' instead of '*radiation energy*' or any other name for the energy of electromagnetic waves. At this early stage, the word 'radiation' will not make things clear to our pupils – particularly since our class experiments on radiation are yet to come – and we should be teaching in a mistaken order if we started referring to waves at this stage. It would be unfortunate if we misled pupils by choosing a name that usually refers to the visible spectrum alone. We must at once explain to pupils that we are thinking of light itself – all the colours red, orange, etc. – *and* some 'invisible light' which our eyes do not notice, such as ultra-violet light and some other kinds beyond the red. As a safeguard, we then put the word 'light' in inverted commas as long as we are using it for some purpose. After pupils have done the class experiments of the 'radiation circus' we might wisely change to *radiation energy*. At the moment, however, we want to keep the naming simple when we are trying to deal with this important and difficult concept.

Here is the kind of introductory discussion of energy that we suggest: 'Mankind uses forces in many ways. Can you think of examples of very big forces? . . .'

Failing enough suggestions, the teacher may need to add some:

Big forces are needed for riveting, for holding bridges together, for supporting tunnels under water, for pulling a train along, etc. And big forces are involved in the smash of a hammer or the starting blast of a rocket.

In some cases, we can get a big force that we need very easily. We can use a lever, or seesaw, as a force multiplier. Think of the force you can get with a pair of nutcrackers, or the force you can get if you use a long crowbar to prise something up. You can get a very big force if you put something in a vice or a small clamp and tighten it up. You can get a very big force just by building a tall pile of sand or lead blocks, or something like that. The pile will press down on the floor under it with a very big force.

Some of those forces do their job for us by just staying there. When we clamp up some pieces of wood in a vice while the glue is setting, or when we build big supports under a bridge to hold it up against its weight, we do not have to go on paying day after day and week after week to keep such forces going. But there are some other jobs that forces do for us (besides supporting things and holding things together) that we do have to pay for, and go on paying for.

If we pull a cart along a rough road we have to provide some kind of pulling agent – a man to pull or push the cart or a horse or a petrol engine, and in each of those cases we have to pay for some stuff to keep the agent going – food for the man, hay for the horse, petrol for the engine. Or, if we want to haul a big load up to the top of a high building, we have to provide fuel for an engine, or food for a man, or something of that kind to get that job done. There are a lot of jobs which need fuel. Those are not jobs in which a horse or an engine just stays still and goes on pushing or pulling without moving. They are jobs in which whoever applies the force *moves along*. We can think of the force moving along, shoving along for a considerable distance. And that, if you think of it, always costs fuel.

The useful jobs which *do* need fuel, or food (or indirect fuel like the electric supply) and cannot just be done at no cost, all ask us for something to get them done – something that costs money but certainly isn't itself money. When we use fuel we draw upon a store of some kind of thing that will do useful jobs, and we call that thing energy.

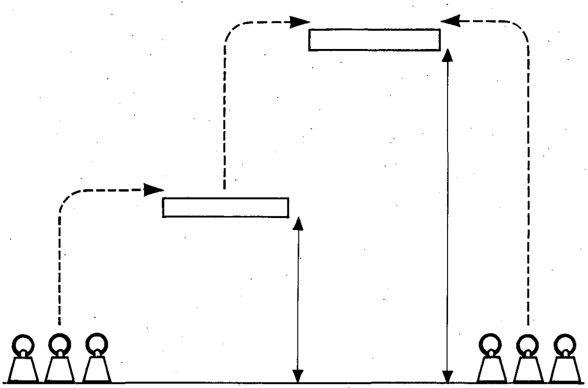
We don't manufacture energy and we don't believe we ever lose any, in the whole world; yet we do shift energy from one form to another. In that way, it is rather like cash. A wise country does not manufacture cash, but there are very important shifts of cash from one person to another, or from a person to a shop, and so on. To get jobs done by a workman, you have to transfer some cash FROM yourself TO him. To get these useful jobs of raising loads done you have to transfer some energy FROM some store of energy in a fuel TO some other form such as the 'uphill energy' of this raised-up weight.

Or we can use the fuel to drive something and make it move faster and faster. You can't make a thing move faster without shoving it along, and then you have [shove] × [distance], some work done, some energy transferred, and this time we say it is transferred FROM the fuel store of energy TO energy of motion or 'motion energy'. Later on we shall call that energy of motion 'kinetic energy, K.E.'. A moving thing has a store of motion energy, and that can be used because we can let the thing be brought to a stop, and in doing that it can haul up a load for us.

WORK

112 Demonstration
Transfer of energy in stages

APPARATUS *item no.*
3 1-kg loads *32*
Tables or shelves arranged to give horizontal surfaces at 1 and 2 m above the floor.



PROCEDURE

The discussion may be as follows:

I want to raise up 3 kilograms, 2 metres. I can simply lift it from the floor up to the top, or I can do it in stages. First I lift 1 kilogram, 1 metre. That costs me a little bit of 'fuel'. I have to draw upon some energy (that I get from my breakfast) stored in chemical form in my muscles. I change it, through my muscles, to some other form stored up in the springy pull of the Earth on this 1 kilogram.

How big is that pull? Yes, it's 10 newtons.

When I move my pull of 10 newtons through this distance of 1 metre, I multiply force by distance and call that 10 newton · metres of work. That is a way of saying how much it costs me. That work (force × distance) is not energy; it's just the way in which I calculate how much energy I have transferred from my chemical store ('breakfast energy') into something stored up in the load. Now I raise it another metre, costing me another 10 newton · metres. The total cost is 20 newton · metres.

What will it cost me to lift another kilogram through this distance of 2 metres? Yes, another 20 newton · metres. And yet another kilogram to make three? Yet another 20 newton · metres. To lift all three kilograms has cost me 60 newtons · metres – and each kilogram costs me the same amount of fuel. This has been tried with very careful measurement on human beings, though the argument behind the experiment is rather complicated.

It will be noted that this is a different treatment of 'work' from usual. This goes back to a more careful use of the term that was established by the great natural philosophers of the last century. It avoids the terms 'work done on' and 'work done by' with all the ensuing doubts about plus and minus signs, and simply says the work is so much, but always adds to that statement 'this is the transfer of energy FROM (such and such a form) TO (such and such a form)'.

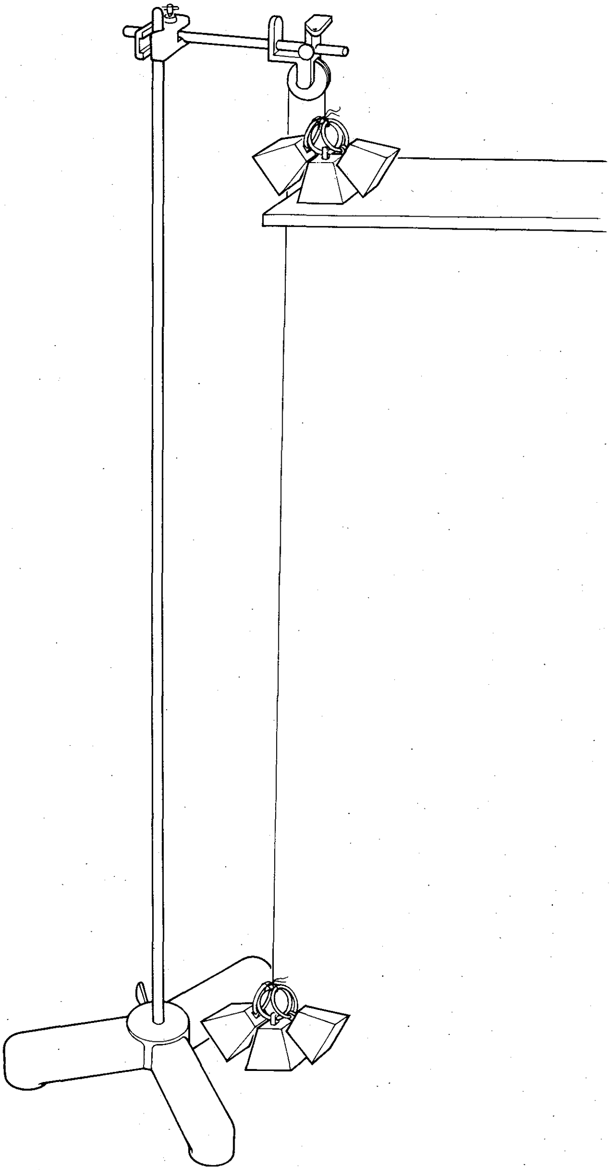
If we always insist on that full statement, we shall find that energy changes are much easier to keep straight.

112X Demonstration
Falling and lifting – an experiment to assist class discussion

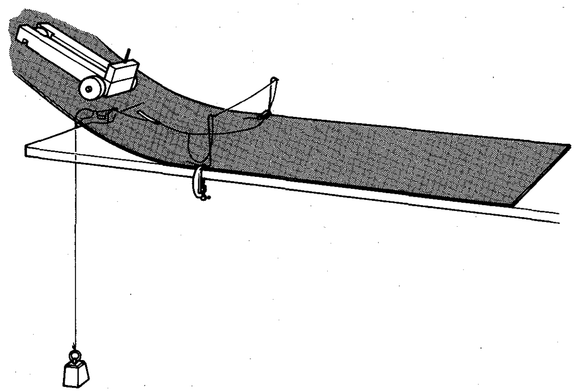
APPARATUS *item no.*
As for Demonstration 112, together with:
2 1-kg loads *32*
1 Weight hanger with slotted weights (100 g) *31/2*
1 Retort stand with boss head *503–504*
1 Single pulley on clamp *40*

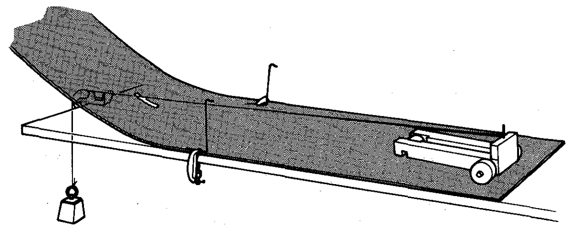
PROCEDURE

The store of uphill energy in the 3-kg load can be made to do something useful by attaching it to a string, running the string over a pulley to another load resting on the floor. This load should be a little less than 3 kg – around $2\frac{3}{4}$ kg perhaps. As the first load falls, the second will rise. Almost all of the 60 newton·metres of energy will be transferred from the one to the other.



stop. The energy has been transferred FROM uphill energy TO motion energy and then FROM motion energy TO uphill energy.





It would be unwise to say that the original store of uphill energy *must* have been converted to motion energy, for that would be just making a rule about Nature rather than trying to find out what Nature does.

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113 'Thought Experiment'
Falling freely

Instead of making the falling load lift another one, it could merely fall. Just before it crashes on to the floor, it will have transferred its store of uphill energy to another form. If we imagine that there is a smooth curved slide at the bottom of the fall the load will move away down the slide and across the floor. If now we could attach a string to it, and if that string ran away over a pulley to another load, then that second load could be raised some distance before the loads come to a

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114 Experiment
Energy change in a crash

As that 3-kg load starts to fall, it has considerably more uphill energy than it will have lower down; but as it loses uphill energy it gains motion energy until it has most motion energy just before it reaches the floor. But there it stops. What happens at the floor?

Pupils will obediently say that the metal gets hot, but they have never experienced such an occurrence.

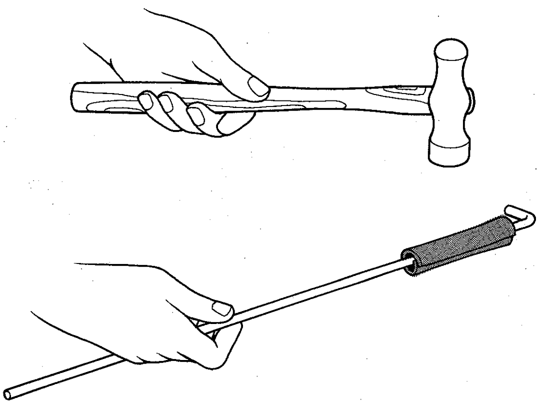
APPARATUS *item no.*

16 Pieces of lead sheet (5 to 6 cm by 1.5 mm or thinner) *10P*

16 Lengths of iron wire (about 25 cm long, 20 gauge) *10Q*

PROCEDURE

The small piece of lead sheet is wrapped round a length of iron wire, which acts as a handle. The pupil holds the other end of the wire and places the lead on an anvil (for example, an iron kilogram weight) on the floor. He hits the lead several times in rapid succession with a hammer as hard as he can. Provided the lead is not more massive than suggested, he should feel the temperature rise.



NOTE

It is often said that lead shows a big temperature rise (and therefore should be chosen for this experiment) because it has a very small specific heat capacity. However, lead also has a large density so that the heat capacity per unit volume is only a little smaller for lead than for other metals. The important characteristic is that lead is inelastic; most of the energy of the hammer is turned into heat by pushing lead atoms beyond the elastic arrangement of the crystal lattice.

The chain of the energy transfer here must be FROM chemical energy in the muscles TO uphill energy of the hammer; then TO motion energy of the falling hammer; and finally TO heat.

Energy and machines

We now discuss machines as energy transmitters. In Year 1 a lever was used in an open-ended experiment investigating the law of the lever. This sort of experiment should now be demonstrated, but with an emphasis on the use of a lever to increase the forces, as a 'force multiplier'.

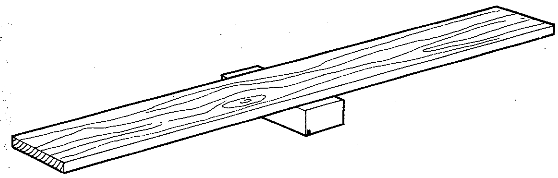
115 Demonstration
Can machines give extra energy?

APPARATUS *item no.*

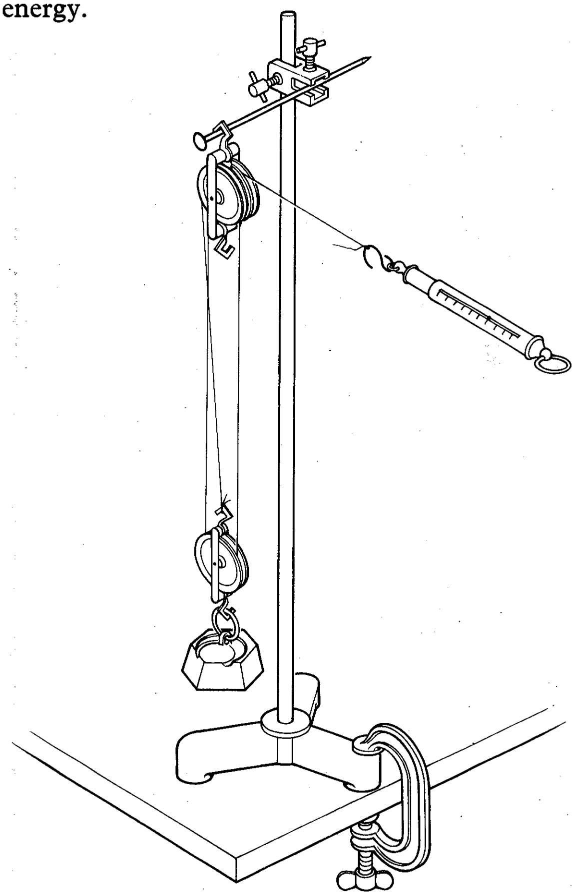
1 Wooden plank (about 2 m long, 20 cm wide, 25 mm thick)
1 Brick or block of wood as fulcrum
1 Single pulley *38*
1 Double pulley *39*
4 1-kg loads *32*
Cord *10A*
1 Metre rule *501*
1 Retort stand and boss *503–505*
1 Large nail *10H*

PROCEDURE

The purpose of these demonstrations is to stress the use of machines as force multipliers and then to examine them from the energy aspect, finding finally that machines do not 'multiply' energy.



a. Set up a large seesaw using a wooden plank (about 2 m long, at least 20 cm wide and 25 mm thick) and a brick, or wood block, as fulcrum. Balance loads in the ratio 10:1 on the two sides of the seesaw. Measure the distance moved by each load when the seesaw is tilted. Discussion will show that there is no 'multiplication' of energy.



b. Set up a pulley system as illustrated. Show that the transfer of energy from one load to the other is about equal even though the loads themselves are different: again show there is no 'multiplication' of energy.

NOTE

In both cases the seesaw and pulley experiments are used as a basis for discussion and not for precise measurements.

DISCUSSION

Suppose I balance the seesaw with a big load here on the left against a small load out there on the right. If I let that load on the right go down, the Earth pulls it down with the weight of that load. Suppose it goes down 10 cm. Then we can calculate the work [force] × [10 cm]. That is the transfer from the Earth's gravitational field, from 'uphill energy' (P.E.) to mechanical energy (strain energy) that travels across the seesaw and turns into a gain of 'uphill energy' (P.E.) in raising the big load on the left side.

If the big load is just ten times the little load and they balance, then its distance from the pivot must be just one-tenth of the small load's distance. If you draw this picture, showing the little load going down and this big load being raised, you can see that the big load at one-tenth of the distance out only rises one-tenth as far as the little load falls. It rises 1 cm; so we can calculate the work of transfer to uphill energy for the big load: [ten times as big a load] times [only one-tenth as big a rise]. So it is the same amount of work.

What you put in with the small force being pulled down a big distance comes out as a big force pushed up a small distance. This machine does *multiply force* for you, but it *does not multiply energy*. You get out just as much energy as you put in.

You'll find that with the pulleys, too. The man pulls down three times as much rope as the rise of the big load, but the big load is three times as big. So the energy transfer from the man is just equal to the energy transfer to uphill energy.

In working pulleys and levers and other such machines, the output energy is not quite equal to the input but is rather less. Discuss the answer to the question: 'Where does the small bit that seems to be lost go to?' Point out that if we wish to make things worse, we can give pulleys poor bearings and then we should actually feel heat being developed with friction there.

ENERGY CHANGES

In Year 1, several energy changes have been investigated (Experiment 57). Teachers may wish to show some of these again. However, we should be careful when we are teaching pupils who have already done Nuffield Physics Year 1 not to give the impression that we are going to show every major experiment all over again, year after year, just because we happen to have the equipment. That is particularly tempting where we have impressive apparatus that is not usually available, such as the steam engine, the 3-dimensional gas model, the fine-beam tube, or bromine diffusion. In the case of each of those examples, there is a good reason for repeating in several different years; but in other cases we should be all the more careful not to repeat too much.

116 and 117 Class Experiments **Examples of energy transfers**

APPARATUS *item no.*

1 Malvern energy conversions kit *9*
1 12-V battery *176*
1 L.T. variable voltage supply *59*
1 Bicycle dynamo assembly *103*
G-clamps (5 cm) *44/2*
For further items, see experiments below.

PROCEDURE

This is a series of demonstrations that illustrate energy transfers. The teacher should show a large number of those listed, naming those forms of energy involved in the transfer. Some teachers will wish to set up the experiments as a 'circus' with small groups of pupils moving from experiment to experiment which they operate themselves. The *Pupils' Text* takes a selection for the two experiments.

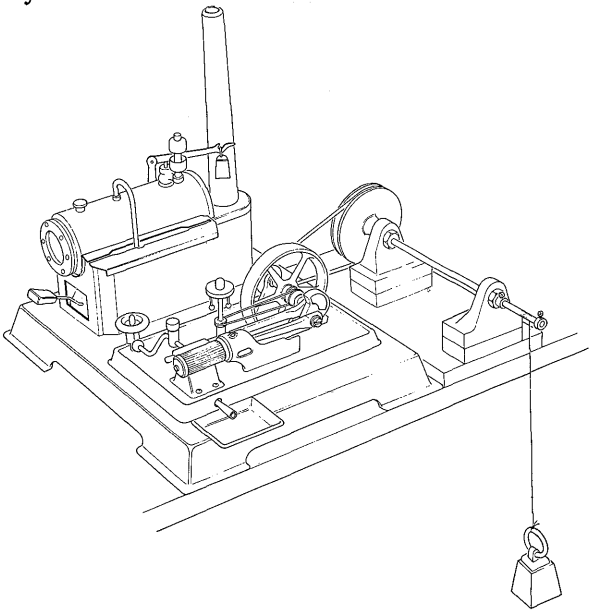
1. Light a match (from chemical energy to heat).
2. Run a Bunsen burner (chemical energy to heat).
3. A model steam engine used to raise a small load (from chemical energy to heat, to mechanical energy in the machinery, to uphill energy in the load).

A model steam engine is included in the Malvern energy conversions kit (item 9I). The makers' instructions for use and care of the engine should be read and carefully observed. It is particularly important to dry out and oil the machinery if the engine is to be stored from year to year.

The steam engine can be operated using solid fuel or the laboratory gas supply. Methylated spirit burners can also be used, but they are not always as effective.

When the steam pressure is up, turn the steam engine by hand until the condensed steam has been expelled. The engine will now run freely.

The engine should be clamped to the bench with a G-clamp and likewise the line shaft (item 9F) next to it. The small pulley on the engine should drive the large pulley on the line shaft by means of a belt or rubber band.



A length of cord should be attached to a weight on the floor (about 500 g is satisfactory) with the other end attached to the line shaft. The engine will raise this load, giving it potential energy which is drawn from the chemical energy of the gas supply or solid fuel.

Note that as the engine is running steadily there is *not* a continuing transfer of energy to spin energy or to K.E. of the rising load.

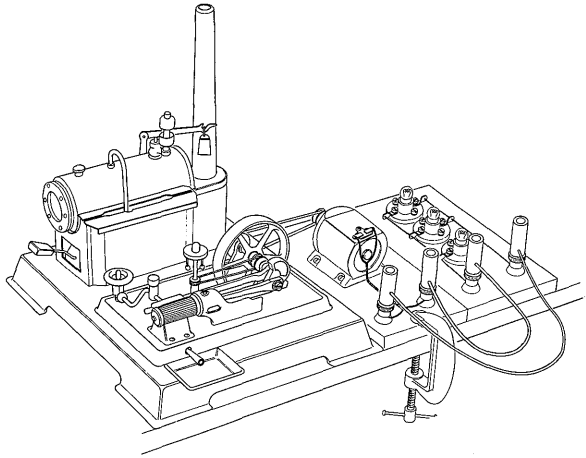
4. A model steam engine accelerating (chemical energy to heat, to mechanical energy in the machinery, to spin energy).

This will raise the question of the kinetic (motion) energy of the moving parts of a fly-wheel. Say that we call that 'spin energy', though it is really nothing more than motion energy of a lot of parts of a wheel that is going round.

Remove the load from the steam engine so that it accelerates.

5. A steam engine used to drive a dynamo which lights a lamp (from chemical energy to heat, to mechanical energy, to electrical energy, to heat and 'light').

The steam engine is used as in (3), the belt or rubber band now being used to drive the motor/generator unit (item 9A). Both the generator and the steam engine should be firmly fixed to the bench with G-clamps.



The output of the generator unit is connected to the lamp unit (item 9D). It will be noticed that switching on and off the lamp produces a change in the mechanical load on the steam engine.

It is effective to use two or three low-voltage lamps in parallel. With all the lamps alight, the engine labours heavily; with none alight, it races. (The lamps may be given a half-turn in their sockets to switch them on or off.)

6. A Bunsen burner heats a piece of platinum until it is white hot (chemical energy to heat, to 'light energy').

7. A battery lights an electric lamp (chemical energy to electrical energy, to heat and light).

8. Grind a handle round against some form of friction brake which develops a lot of heat (from chemical energy provided by food to heat). The friction calorimeter unit (item 9H) is suitable for 'circus' work.

9. A balloon is blown up and then released (springs energy of the stretched rubber to motion energy).

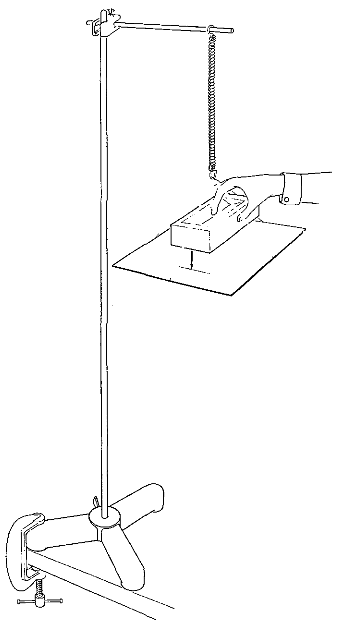
10. A brick is suddenly hung on a spring (uphill energy to motion energy, to springs energy – and then to and fro among the two last).

The compression spring (item 88) is hung from a retort stand firmly clamped to the bench. A simple hardboard platform about 30 cm square is hung from the end of the spring by four strings so that is horizontal.

A load such as a brick is held just over the platform and released suddenly. The changes in energy are observed. Alternatively, the weight is hung on the string and held by hand with the string unstretched, then released.

11. Torsional pendulum (oscillating to and fro between spin and springs energies).

The arrangement used in (10) can be used as a torsional pendulum. The vertical motion is stopped and the platform given a twist.



12. Thermocouple and galvanometer (heat to electrical energy, to heat in the wires and springs energy in the hairspring).

A piece of iron wire (about 24 SWG) about 75 cm long is attached to two similar lengths of bare copper wire (also about 24 SWG) by twisting the ends together. The free ends of the copper wires are connected to a demonstration galvanometer with, if necessary, a resistance box in the circuit. One of the two junctions is kept cool in a beaker of water at room temperature whilst the other is heated gently with a flame. (About 1500 μV is the maximum likely to be reached.)

13. Fuel cell (if available) (chemical energy to electrical energy).

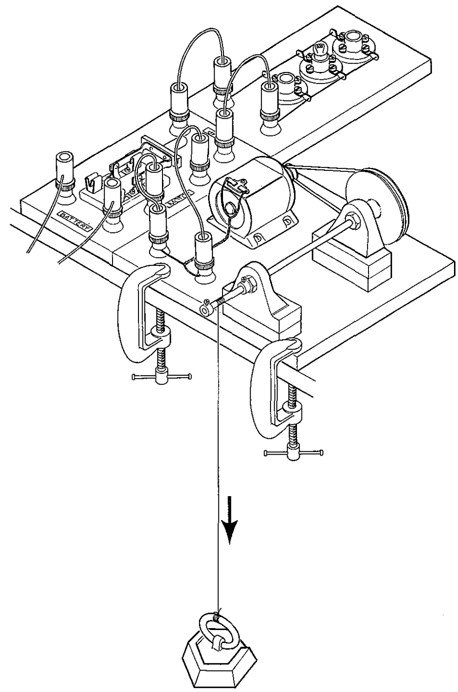
14. 'Inertia operated' toys (spin energy to motion energy to heat); and clockwork toys (springs energy to motion energy and heat).

15. Hammer and nails (chemical energy from food to motion energy and to heat).

16. Model pile driver (. . . to uphill energy to motion energy to heat?).

17. Battery runs an electric motor which lifts a load (chemical energy to electrical energy, to mechanical energy, to uphill energy).

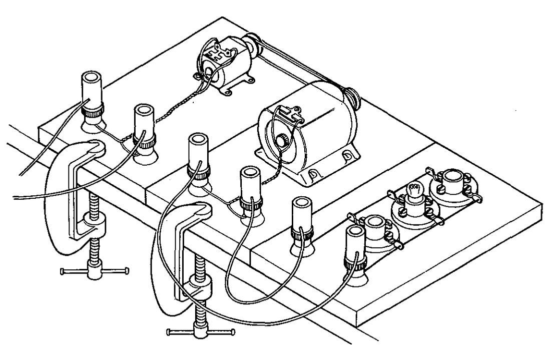
The motor/generator set (item 9A) and line shaft unit (9F) are clamped next to each other at the edge of the bench and the pulleys on each connected with a driving belt. One end of a metre of cord is secured to the axle of the line shaft and the other to a load of 1 kg. When 4–6 V d.c. from a battery are applied to the motor, the load is raised.



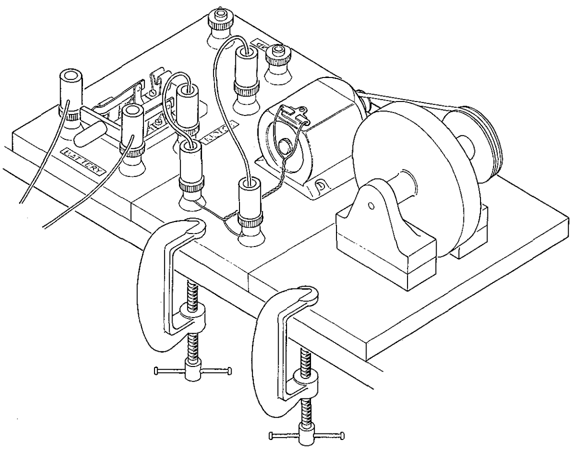
18. A falling load drives a generator and lights a lamp (uphill energy to mechanical energy, to electrical energy, to heat and light).

The circuit is a development of that used in (17). A two-way switch unit (item 9C) is connected so that when the load has been raised, the switch is thrown and the battery disconnected whilst the motor/generator unit is connected to the lamp unit (item 9D). As the load falls, the lamps will light.

19. A battery runs a motor which drives a generator which lights a lamp (chemical energy to mechanical energy . . .).



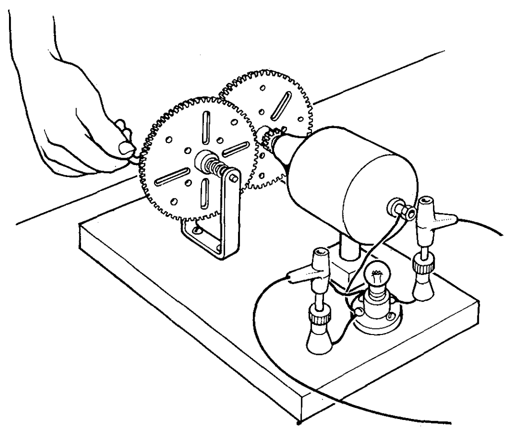
20. A battery runs a motor which drives a fly-wheel (chemical energy to mechanical energy, to spin energy).



In this arrangement, if the switch is thrown, the spin energy stored in the fly-wheel can be used to drive the generator and to light a lamp.

21. A dynamo driven by hand lights a lamp (chemical energy to mechanical energy, to electrical energy, to heat and light).

The bicycle dynamo assembly (item 103) can be driven by hand at high speed in order to drive the lamp attached to the assembly.

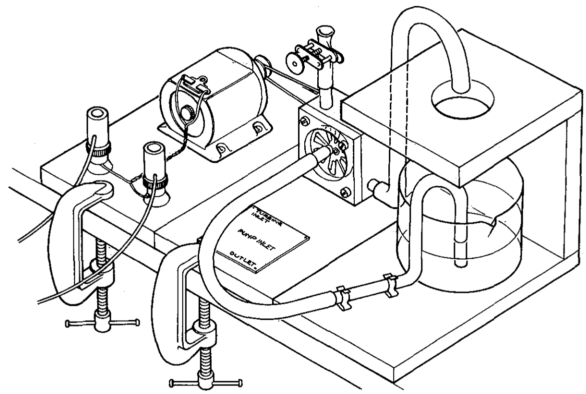


22. A spring gun fires a bullet (springs energy to motion energy).

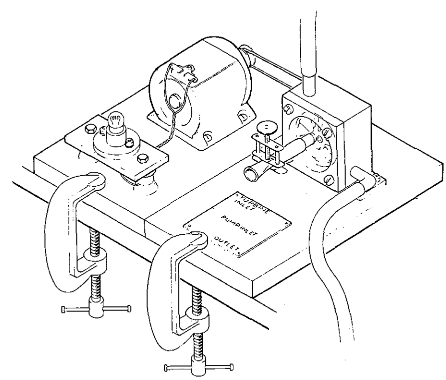
23. Hammering lead (motion energy to heat).

24. A pump raising water (electrical energy to spin energy . . .).

The motor/generator unit (item 9A) is clamped next to the turbine/pump unit (item 9J), which in turn is next to the head of water unit (item 9K). When 4–6 V d.c. are applied to the motor, it drives the pump unit which takes water from the lower level to the higher one. (It is necessary to prime the pump by filling with water before use: this is easily achieved by sucking on the third connection to the pump unit with a finger over the output, and the input under water.)



25. A water turbine driving a dynamo, which lights a lamp (uphill energy to motion energy . . .).



The turbine/pump unit (item 9J) is positioned next to the motor/generator unit (item 9A) and both are clamped rigidly with G-clamps. The pulleys on the two units are connected with an 8-cm rubber band. The output from the generator is connected to a lamp unit with one lamp. The water from the mains enters the turbine at the top and the pressure drives the turbine blades round, which in turn drives the generator. If the water pressure is not very great, some form of force pump will be necessary to increase the pressure.

26. Acid added to alkali produces heat (chemical energy to heat).

27. Photographic exposure meter in which light causes an electric current to flow (light energy to electrical energy).

'Light' energy (radiation) Some of these examples raise the question of radiation energy. We simply say light and ultra-violet light and wireless waves and some other things like that do carry energy, and carry it very fast. We get a great deal of energy from the Sun; and that comes by radiation. Some of it is light that we can see, but most of it something that is much the same except that our eyes do not respond to it.

Energy transmitted through a vacuum? Ask if energy can travel through a vacuum. Tease pupils who say 'No' by asking whether a rifle bullet carries energy; and whether it can move through a vacuum. Then ask whether energy can move through a vacuum without any actual stuff (bullet, air, electrons) moving? What does move, that is not actual stuff rushing along with the full motion? Suggest waves. Ask what kinds of waves pupils know. Suggest sound waves. See whether sound travels through a vacuum.

118 Demonstration
Energy through a vacuum?

APPARATUS *item no.*

1 Vacuum pump *13*
1 Clapper bell in round flask *87*
1 Reel of nichrome wire (26 SWG) *57G*
1 Voltage supply *59*
1 Bourdon gauge *67*
1 T-piece
1 Hoffman clip *10V*
1 Rubber bung to fit flask

PROCEDURE

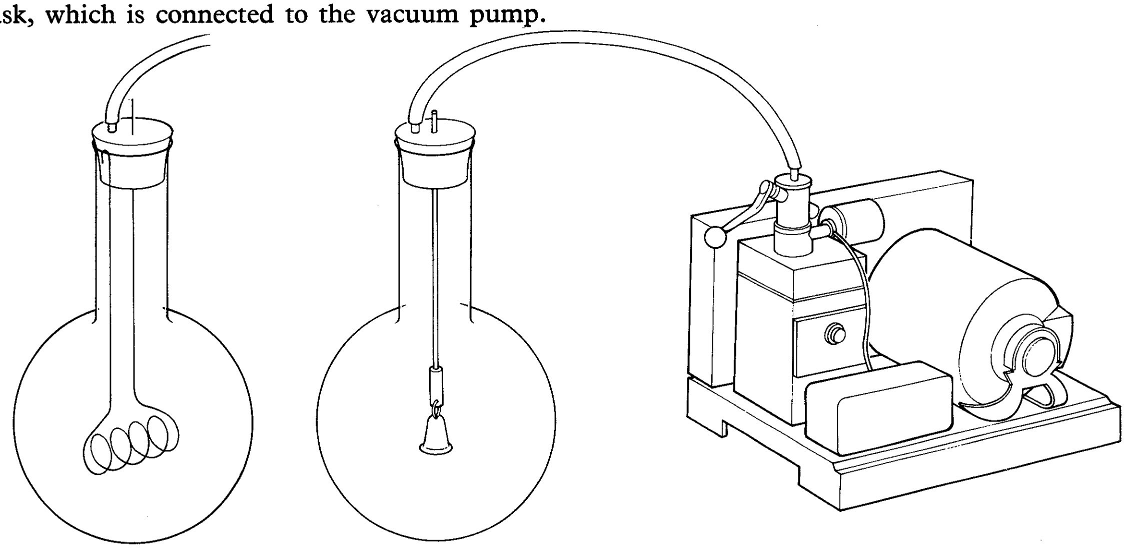
a. The clapper bell is wired to the rubber tube, by which it is suspended inside the large bolthead flask, which is connected to the vacuum pump. The bell is rung by shaking the flask to and fro and the sound is heard. The flask is then evacuated and the sound is no longer heard. Then air is readmitted.

b. Remove the bell and fix a coil of nichrome wire inside. Connect to the variable voltage supply. Turn up the voltage until the filament glows. Then pump the air out. The glow will be brighter as there is no longer heat loss by convection.

It should be shown that air has been pumped out by connecting a Bourdon gauge through a T-piece.

The simple form of demonstration with sound is just as good as the more modern one that uses an electric bell and it is less distracting. It is a somewhat misleading experiment because in fact the sound grows fainter as the air grows thinner, not because the few remaining molecules cannot carry sound but because the 'impedance match' between the bell and thinner air is so much poorer that the sound cannot get from the bell to the thin air.

Discussing energy transfers Discuss with pupils energy transfers in a lot of examples such as the following. At this stage it would be unwise to do this as a lecture in which we *tell* pupils what happens. However halting, the story should come from the pupils. We may have to make a ruling from time to time in order to avoid building up unsound knowledge (see note below on heat energy of gases), but in general, we should accept pupils' versions. We should certainly encourage them to continue the changes back and forth.



For example, if we discuss the change in a Bunsen burner that heats a lump of metal white-hot, we may say 'from chemical to heat and "light" energy', but pupils may want to go on and trace the radiation on across space to an absorbing wall where it produces heat; and other pupils may want to trace the radiation back to the sunshine that helped the growth of trees, to make the coal from which we get the gas for the burner. Such straggling streams of red herrings, usually unwelcome in a well-organized class, can do nothing but good here.

Here are specimens, for each of which we should ask pupils to describe the energy changes:

a. Drive a car uphill. (From chemical energy of petrol + oxygen to gain of uphill energy + . . .? . . . a possible thought about heat.)

b. Drive a car faster and faster along the level, accelerating from rest. (From chemical energy to motion energy + . . . ?)

c. Let a moving car coast to a stop on a level road. (From motion energy to heat. Where? Some in the tyres and road, but some in the air.)

d. Let a parachute descend slowly and steadily. (From uphill energy to heat in the air, via some temporary motion energy of moving whirlpools of air left in the wake. Some pupils will say from uphill energy to motion energy, but we must point out that once the parachute has reached a steady speed, it is gaining no more motion energy.)

Now return to the question of a car driving uphill or accelerating along the level, or even driving steadily along the level. Does the car turn any energy into heat by stirring up the air as it goes along? Obviously, yes: energy released from its fuel goes partly to other motions, wholly so in the case of steady speed along the level.

Note on 'heat energy' of a gas When a confined gas is heated, it gains energy in the form of increased molecular motion. Some of that is kinetic energy of random motion of molecules, but in all gases except monatomic ones there is also a gain of rotational energy and sometimes of energy vibrations as well. That is all the heat energy of the gas consists of: there is no store of potential energy except, of course, P.E. of the (P.E. + K.E.) of vibrational motion. Pupils sometimes think of a gas at high pressure as being like a compressed spring with strain energy. There is no such strain energy.

If we compress a gas by pushing a piston quickly into a cylinder, the gas grows hotter, and all the transfer of energy from us to the gas goes into energy of molecular motion. If we let the compressed gas cool back to the original temperature, it loses all the energy that it gained, so all the energy that we transferred to the gas now goes out to the outer world. The compressed gas, back at the room temperature, has no extra store of energy because it is compressed. Yet we can still make it transfer some energy to other things by letting it push a piston out with its high pressure. True, but the energy it then delivers will be supplied by the gas cooling down below room temperature.

Heat

Trace the energy changes of a car that starts, goes faster, along the level, and uphill, then slower, then faster, and ends up at a stop again. What are the initial and final forms? Leave this question to brew in children's thoughts, but lead them in the course of time to the conclusion that all the energy of the fuel, petrol + oxygen, ends up in the form of heat in warmer air. (Unless, of course, the whole trip is from bottom to top of a mountain, in which case some of the energy does end up as stored potential energy.)

Then ask about a man who climbs a hill, and another who walks along the level. The latter transfers some food energy to heat in the air by stirring it up just as a car does, though on a very mild scale because he walks slowly. But he also turns a lot of food energy into heat in himself when he is walking. In fact, the human body is at best 25 per cent efficient: for every chunk of energy transferred to some useful form there are three chunks of energy transferred to extra bodily heat that has to be wasted as heat to the air. So the walking man heats the air quite a lot – about four times as much as a walking robot of the same size driven by electricity. And the mountain climber, by the time he has come down the mountain again, has transferred a good deal of energy from his food store of chemical energy to other forms, all of it in the end to heat.

So far we have just been naming and discussing and demonstrating some forms of energy and changes between them. We should point out that in many other chains of energy changes that are important in the world the final form of the energy is heat: so that the air gets warmer by a very small amount. From the energy point of view, the aeroplane that has made an enormous trip and comes back to its starting place has ended by transferring all the energy stored in fuel it uses into heat, somewhere in the world's atmosphere. Of course, there are exceptions: if I lift a brick from the floor up to a high shelf and leave it there, I have transferred some food energy into potential energy which will stay there as long as I leave the brick.

Note that in many cases it is the *changing* of the energy that matters to us: the *changing* from food energy to potential energy when we haul up a load of bricks; the *changing* from strain energy in the wound-up spring of a clock to other forms – ultimately heat – as the clock runs. In other cases, it is the *final form* of energy that is interesting to us; as in heating some bath water.

Transfer to heat When we use a coal fire to heat water for a hot bath, we transfer energy from 'chemical' form in the coal + oxygen to 'heat' in the water. There it is the actual energy in its final form, heat in the water, that we feel is important.

Work and indirect measurements of energy transfer

Often (though not always) an energy change involves a measurable force pushing something along through a measurable distance. In such cases we can multiply that force by that distance, and calculate the *work*, the energy transfer in newton metres (which we call joules).

Later on, we shall be able to calculate energy changes into kinetic (motion) energy, which will be very useful to us in atomic physics. However, there are other cases, like the heating of bath water, where no tangible force shoves through a measured distance; so we cannot calculate the work, but then have to go at things more indirectly. We have to say, for example:

If we made the heat for the bath water by shoving a rough block of wood along a rough table, instead of using fuel, how big a force would we have to shove with, for how far, to get enough heat for that bath water?

We could do an experiment to find out, but it would require an enormous amount of shoving rough blocks along a table to heat even the smallest lot of bath water – like the child who thinks he can easily light fires by rubbing two sticks together. However, that has been done (by Joule himself). And when we try to keep track of the energy changes in those indirect methods we find that the cost of energy change of heating the bath water seems to come to the same amount whatever way we go about it. So we think it is all right to measure energy changes indirectly when we have to, though we are really taking it for granted then that energy never gets created or lost. If so there is no danger in going by a roundabout process.

119 Class Experiment
Climbing stairs

Every pupil should climb a flight of stairs (not with a clock to time the climb – that comes later, when we measure power) and calculate his transfer from food energy to potential energy for that climb, just making a rough estimate. That is a gain of useful potential energy because up at the top of the stairs he could be tied by rope and pulleys to some load that had to be raised or to the axle of a dynamo to be driven, or he could do some other useful job that requires energy transfer. However, we should tell pupils now, and remind them later, that when muscles draw upon chemical energy supplies they only transfer about one-quarter of the total to useful forms such as P.E.: the other three-quarters is transferred to heat – extra waste heat. They should calculate how much they transfer altogether in that stair-climb to other forms, including waste heat.

Each pupil will need to know his or her own weight in newtons and a tape measure should be available for estimating the height of the stairs.

A zero for uphill energy? If the flight of stairs used is part of a long staircase, it is worth while to ask questions about pupils who begin their climb from different levels and to make it clear that we can only talk of differences in uphill energy.

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120 Class Experiment
Transferring a joule

APPARATUS *item no.*

1 Forces box *63*

PROCEDURE

Pupils may pull the string labelled 1 newton to its fullest extent of 1 metre. Then they will have transferred 1 joule of energy FROM chemical energy TO uphill energy – they have exerted a force of 1 newton through a distance of 1 metre.

CHAPTER 14

Warming things up

What happens to temperature, to length, to state?

We now touch on heat, measured by a weighed mass of water and a thermometer. We see some of the effects of heat – where possible in class experiments – but we should not spend too long on them.

Conservation In these discussions we tacitly assume that energy is conserved. This is not the time to question that and make pupils feel that they – or we – are not quite sure what we are doing with the energy. The whole discussion of energy is new and complicated and we had better blandly assume conservation at this stage.

Yet, the teacher should always keep in mind this warning, that we are at present – just for present teaching – assuming the complete conservation of energy. At a later stage, we shall go back and show pupils that that is not just a dogmatic belief but is in considerable measure based upon experiment.

It is good for children to know about the conservation of energy and to have growing understanding of it. And here we are giving that by taking conservation for granted at first – just as both scientists and children have long taken the conservation of mass for granted – but we should keep a warning flag there in our own minds as teachers and issue an occasional comment to children to warn them that we must show why we believe conservation is supported by experiment. The pupils should know that the flag is there.

We should be particularly careful not to offer the remark, 'You can't get something for nothing' as support, still less proof, for conservation of energy. That remark does apply to some things such as momentum and cash, but not to others, such as force, pain. It is only *after* we are convinced by experiments, etc., that energy *is* conserved that we can safely apply that remark to it.

Units for heat In Year 4, we shall examine the evidence of the great series of nineteenth-century experiments done by Joule and others in which interchanges of electrical energy, chemical energy, mechanical energy, and heat were shown with increasing certainty to support a general conservation of energy.

Until that case is clear, we shall be well advised to use a different unit for the few thermal measurements we shall make from the unit established for mechanical measurements. Otherwise, as pointed out in the 'Note for teachers on conservation of energy' in the *General Introduction*, the testimony in favour of conservation would be given in a series of numbers in the strange units joules/joule.

For the few heat measurements we shall make, we shall therefore use an arbitrary 'thermal unit', which is, in effect, the kilocalorie. We shall install a rule for measuring heat exchanges: let the heat warm up some water and multiply the mass of water (in kilograms) by the temperature rise (in Celsius degrees).

Temperature We treat the effects of heat quickly and simply; so we shall not discuss temperature, 'measured hotness', in detail. We say it is the thing that the thermometer measures and point out that some thermometers use the expansion of mercury 'to show how hot the thermometer itself is'. Others use different things which change with warming, such as resistance of a wire, or voltage generated by two different metals joined together. Ask whether one can be sure these different types of thermometer will agree with each other. Warn pupils that we cannot expect that, but must just choose one standard type. In fact, we agree on mercury in glass for ordinary purposes because it is convenient, agrees well, by good luck, with our standard gas thermometer, which in turn agrees with the absolute thermodynamic scale.

Mercury thermometers Mercury has some practical advantages over some other liquids, such as visibility, and a wide range, and lack of surface-tension troubles. Its relatively small coefficient of expansion is an advantage, because it makes exposed-stem errors less important.

We should never say, 'Mercury expands uniformly' in listing its advantages, since that is automatically true if the expansion is compared with temperature by a mercury thermometer; so, as pupils interpret it, the remark is a silly one. The only sensible form would be to say that the expansion of mercury happens to agree more closely with that of gases than does the expansion of most other liquids.

These 'advantages' of mercury do not need to be discussed with pupils; we should rather adopt an attitude that we can choose any reasonable system we like for measuring temperature; and we happen to choose a mercury thermometer for convenience, and shall probably change to a better standard later on.

We start without explaining fully what we mean by heat, asking the pupils to find out what five minutes' heating with an electric heater (running at 12 V) will do to water. We simply say that we know we have to run the heater and pay for the electric supply (or pay for something equivalent) to warm the water up. And we think, by common sense, that the more water to be heated, and the hotter we want it, the more we shall have to pay. We give the name 'heat' to the thing we give to the water, the thing that warms it up, the thing we pay for. Long ago, scientists and engineers decided to measure that thing, heat, by giving it to water, weighing the water and measuring the rise in temperature which resulted and multiplying the results. We announce that measuring scheme, and suggest the question: 'How much heat does your electric heater supply in five minutes?'

121 Class Experiment
Warming water

APPARATUS *item no.*

- 8 Immersion heaters *75*
- 8 Aluminium containers *76*
- 8 Lever-arm or spring balances *42*
- 8 Thermometers (−10 to 110 °C) *542*
- 8 Stop-clocks or stop-watches *507*
- 8 Transformers *27*

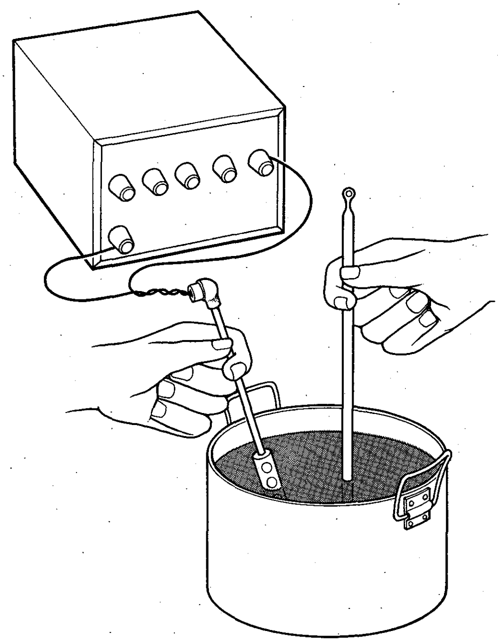
The immersion heaters are 12 volt, 60 watt. They therefore require 5 amps and this can be supplied from the transformers.

121a

PROCEDURE

We ask the pupils to heat 1 kg of water in an aluminium saucepan. They should take the temperature of the water before starting, run the supply for 5 minutes, stirring constantly, then turn the supply off and continue stirring and take the highest temperature.

Measuring the amount of water by *volume* would probably cause confusion in any later experiments involving specific heat capacity. Even though we ask pupils to use so many grams of water, we risk confusion if we then provide measuring cylinders. It is much wiser to spend extra time on quick weighing with spring or lever balances. (Unfortunately, the lever balance has a limit of 1 kg, so pupils cannot just weigh an empty saucepan and then add water until an extra 1 kg has been added. Instead they should weigh a beaker, add water until they have 0.5 kg of water in the beaker, by weighing, and put that in the saucepan. They then add another 0.5 kg to the saucepan. Alternatively, they may place a smaller mass of water in the saucepan; but this will lead to more trouble over arithmetic in the end.)



Now ask the pupils to apply the rule to find out how many of the 'thermal units' are delivered by the electric heater to the water.

121b

Next ask pupils to find out how many 'thermal units' are delivered by the electric heater (running on the same supply) in 5 minutes to half as much water, 0.5 kg.

Ask pupils what would happen if they did the experiment starting with quite hot water. Would that be an accurate and reliable experiment? In the light of the answer to that, was their original heating experiment likely to be completely reliable and accurate? (We should give pupils a sense of concern about heat loss from the very beginning.)

Discussion of 'heat delivered' Collect answers to the questions: 'How many thermal units did your heater deliver to one kilogram of water in 5 minutes? How many to half a kilogram?'

In most cases, the answer to the second question will be roughly similar to the answer to the first, suggesting that our multiplying rule does give a suitable measure.

Of course the two results will not be equal, because we have not allowed for the aluminium saucepan; and in any case heat measurements like this are beset with serious troubles of heat losses. (That is why we suggested raising the thought experiment of starting with much hotter water.)

Careful allowances for the saucepan, and elaborate precautions to reduce heat losses might make the experiment more accurate, but they would not make it clearer. In this case, it is better to warn pupils straight away that there are heat losses and that therefore the experiment is only a very rough one. Yet we should point out that it could be made, and has been made, very much more precise – though that would need some information which we do not yet have concerning the behaviour of aluminium.

It is possible to conduct the experiment with water in a container of negligible thermal capacity: a plastic bowl or even a polythene bag. The risks of the latter breaking are so great that we do not recommend it as a class experiment. The disadvantage of the former is that the results are so good that the important question of 'heat loss' is not even raised.

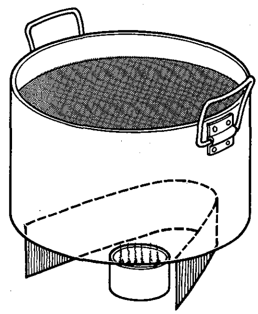
Assuring pupils that the differences we have found are due to difficulties of measurement, we arrive at a rough estimate of the heat, in thermal units, delivered by 5 minutes' worth of running the electric heater.

121c
Bunsen burner

If time and interest permit, we may ask pupils to find the heat delivered by a Bunsen burner running for one minute under a saucepan with 1 kg of water. Unfortunately, we cannot compare costs of heating – electric supply *v.* gas – because we have neither a voltmeter at this stage nor a gas meter.

121d
Alcohol flame

If time and interest permit, pupils may try heating 1 kg of water with a small spirit flame, using 1 cm^3 of alcohol in a small cup pressed out of aluminium foil, or in a tiny beaker. The same saucepan with 1 kg of water must be supported about 5 cm above the small alcohol flame. For that, a strip of tin sheet about 10 cm wide, bent into a vee or a circular arc, will serve as support for the saucepan and a wind-shield for the flame. One cubic centimetre delivers, when burned like this, about 4.5 thermal units to a saucepan of water.



All the experiments above are aimed at giving a general feeling for heat and its measurement. They should not be extended to take up much time, nor should the obvious inaccuracies be discussed at length. In modern teaching of chemistry, considerable attention is paid to calorimetry; and we shall want pupils to regard heat as something that they can, in principle, measure when we discuss conservation of energy fully in Year 4; but that requires a general idea rather than a knowledge of techniques.

However, some pupils will themselves have raised the question of heating up the aluminium saucepan as well as the water, and we should now tackle that question and make a simple introduction to specific heat capacity in a class experiment.

Specific heat capacity: introduction and estimate

Ask pupils to feed energy from the electric supply to the form of heat in a block of aluminium.

122 Class Experiment

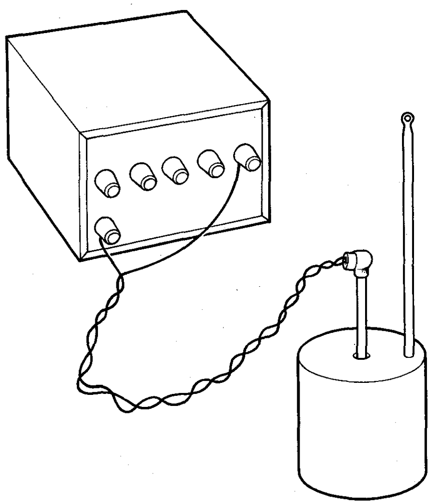
Warming up aluminium

APPARATUS *item no.*

8 Immersion heaters *75*
8 Aluminium blocks *77*
8 Thermometers (− 10 to 110 °C) *542*
8 Lever-arm or spring balances *42*
8 Stop-clocks or stop-watches *507*
8 Transformers *27*

PROCEDURE

The aluminium blocks are weighed on the balance and then the thermometer and electric heater are inserted in the appropriate holes. The heater is then connected to the 12-V supply and switched on for 5 minutes as in Experiment 121. The maximum temperature rise is noted. (The heater must be run on the same supply as in Experiment 121.)



NOTE

Oil in the thermometer hole in the aluminium blocks will help thermal transfer. It is not necessary to put oil with the immersion heater.

DISCUSSION

We should tell the pupils that they may take it for granted‡ that neither the heater nor the electric supply authorities can tell whether it is water or aluminium, or even air that is being heated; so they may take it for granted that the heater delivers the same amount of 'heat' in each 5 minutes. That is a large unsupported assumption, which we should offer in an apologetic tone.

If we could provide voltmeters and ammeters and if pupils understand their use, we could make that assumption *seem* well supported; and if we provided joulemeters instead, we could give an even simpler and stronger sense of assurance. Yet we should be taking conservation of energy for granted, implicitly, just as much as in the present suggested treatment. The measuring instruments would only tell us that the heater is running at the same level, in each case, so far as the electric supply is concerned. So we suggest that teachers should be content with a simple experiment, resting on a temporary assurance that the heater delivers the same heat in 5 minutes whatever it is heating.

If pupils follow the method used for water, of multiplying mass by temperature rise to calculate the heat gained in thermal units, they will find that this disagrees seriously with the result they had for water. They should *assume* the water experiment's result applies to the heater in this case too and find the 'extra factor' that must be used to make the new answer agree with the old one. (The assumption there is the weak point of this whole experiment; and it would be just as weak – though it would not seem so painful – if pupils had instruments to assure them that the heater is running at the same rate.)

Calculating [mass] × [temperature rise], pupils find that a block of aluminium seems to take much fewer 'thermal units', much less heat, to heat it up through the same temperature rise, so we give aluminium a special number, to show its 'appetite for heat'. Instead of multiplying mass by temperature rise, as for water, we multiply mass by temperature rise and *then* multiply by that special number to find how much heat is needed. Working backwards from that idea, we ask pupils to calculate the special number for aluminium. We explain that we call this the 'specific heat capacity' of aluminium and consider it a useful number to know. They will not obtain an accurate value such as 0.2. This is an 'experiment of principle' to enable pupils to meet the idea of specific heat and learn how it *could* be measured. (We may also tell pupils the result of more careful measurements, about 0.2.)

Remember, we actually heated an aluminium saucepan as well as the water in the first experiment, and now

‡ 'They did not take it for granted, but concocted four plausible theories to explain why the aluminium got hotter than the water.

1. Heat travels more quickly through aluminium than water
2. Heat comes out of the heater more quickly in aluminium
3. More electrical energy is used in the case of aluminium
4. Aluminium takes less heat to warm up

They devised tests for each.'

we can go back and find how much heat went to the saucepan, by multiplying its mass by the temperature rise (much the same as for the water) and multiplying by the extra factor 0.2 as well.

In asking pupils to do this experiment the teacher should remember that this is an *exploration of energy measurements* and not an attempt to measure specific heat capacity with any great precision. We give the 'official' value to pupils; yet they should not be encouraged to think of their own experiment as inferior and 'giving the wrong value', like a black market exchange, to be obliterated by the right value.

We shall not make further measurements of specific heat capacity. Pupils could have an interesting time making careful measurements of different specific heat capacities with electrical heating but we shall not need these in this course; so that is a part of physics which we shall omit in order to save time. Specific heat capacities are of use in applied physics, though they are not used as often as one might expect. In modern physics they are not of much interest until one reaches a study of their changes with temperature, which suggest quantum effects. Then they are indeed illuminating.

Other ways of warming things up We have used an electric heater to raise the temperature of some water and of a block of aluminium. In Experiment 114, pupils investigated the transfer of energy from the motion energy of a falling hammer to a piece of lead and observed that the lead was warmed up.

Ask what happens to the motion energy of a moving bicycle or motor car when the brakes are applied. Working against friction produces heat in quantity.

In diesel engines, the oil and air mixture in the cylinder is fired by a sudden high compression, which raises the temperature, almost like the sudden hammer blow on the piece of lead.

Gases: 'heat a mode of motion'

Now that we think of heat as a form of energy, we can ask, 'What happens when heat is given to a gas, which we already think of as made of rapidly moving molecules?' They make gas pressure by bouncing against the walls of their container. 'If we keep a gas in a closed container and heat it up, what happens?' Children will guess that the pressure grows bigger, and therefore the bouncing effect grows bigger.

How can a number of gas molecules bouncing about in a closed box bounce harder? What *must* have happened to them when we heated them up?

Elicit the answer 'moving faster'.

For a short class experiment give pupils the gas model of marbles in a tray and ask them to try 'changing the temperature'. If, in a hotter gas, the molecules are moving faster, ask: 'What kind of energy do they have more of?' Elicit the answer 'motion energy'.

123 Class Experiment
The marbles model of a gas

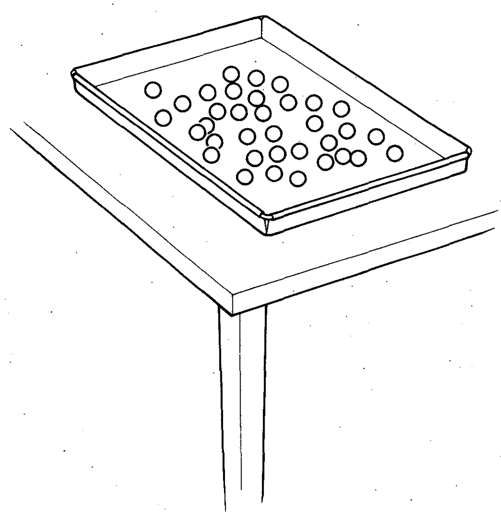
APPARATUS *item no.*

1 Two-dimensional kinetic model kit *12*

The kit contains 16 metal trays enabling pupils to work in pairs.

PROCEDURE

Each group should have 20–24 coloured marbles – these are included with the kit and are the standard size of toy-shop coloured marbles, about 15 mm in diameter. It is important that these are coloured so that the pupils can concentrate on a particular marble if they wish.



Pupils keep the tray in random shaking motion sliding it on the table.

This is an extension of Experiment 48 in Year 1. On this occasion, they should also agitate the tray more vigorously to illustrate the relationship between faster motion and change in pressure.

At this stage, if interest permits, we might mention the possibilities that molecules acquire other forms of energy – spin energy and vibration energy – but for most pupils it would be better to keep those out of the picture at this stage, so that we may for the moment think of heat going into a gas to make the molecules move faster, increasing their individual kinetic energies of random motion. Temperature which we have not tackled clearly so far, but have merely taken as the thing given by a thermometer, may well be connected with the kinetic energy of gas molecules. Some such remark to foreshadow what is coming next year might be a help.

OTHER EFFECTS OF HEAT

In the past the effects of heat often received a good deal of attention in the teaching of physics to younger pupils. In this course we propose to treat them more simply and quickly, not because they are poor things to teach but only because we need to restrict our material to give time for careful teaching in other regions. Professional scientists will need to study them in much greater detail. But in this course of 'Physics for all', we aim at giving pupils an acquaintance with thermal properties but not at giving them considerable details of either theory or practice. Acquaintance will suffice in this course, particularly if pupils make it by their own experimenting. So the following experiments are meant to be done briefly, as far as possible as class experiments.

Expansion of solids

This should be treated qualitatively without precise measurements or calculations.

124 Class Experiment
Expansion of a metal bar

APPARATUS *item no.*

8 Iron rods (about 60 cm long, 6 mm diameter) *57Q*
16 Wooden blocks
8 1-kg masses *32*
8 Needles *53D*
8 Drinking straws *53A*
8 Bunsen burners *508*
8 Microscope slides *3G*
8 $\frac{1}{2}$-kg weights *36*

PREPARATION

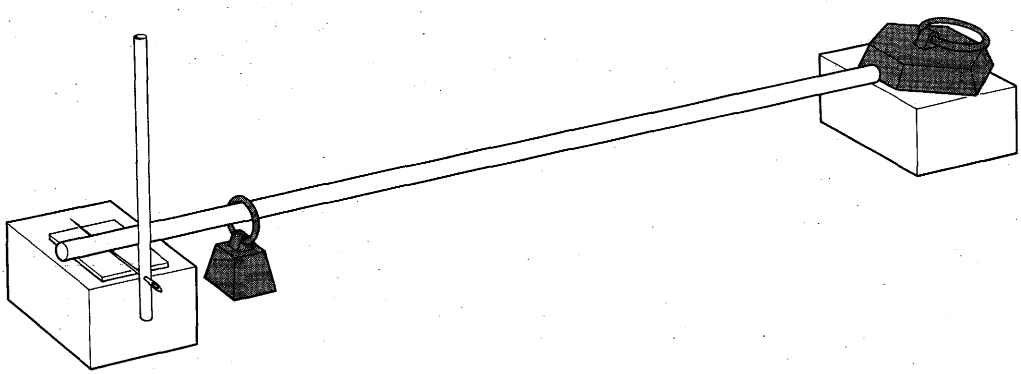
The length of rod is supported as shown on the two supports and is prevented from moving at one end by the 1-kg mass placed on it. The other end can roll on the needle which rests on a small piece of glass (e.g. a microscope slide) placed on the block. The drinking straw is impaled upon the needle.

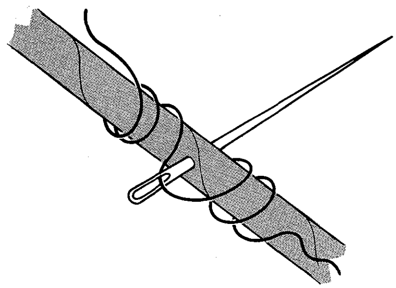
When the rod is heated by moving a Bunsen flame along it, the straw will move with the rolling needle.

If the rod slips on the needle, hang a load on it near the needle.

NOTE

If the straw slips on the needle, run a short piece of fine copper wire through the eye of the needle, and wrap it round the straw.





PROCEDURE

Ask pupils to heat the rod and see what happens. This may seem to teachers who are familiar with careful measurements of expansion a mere piece of play. If one tries it with young pupils, one finds that this simple experiment, not obscured by worries over a micrometer gauge and its techniques, is something that pupils enjoy and learn from. This is not the time to argue whether one revolution of the straw means an expansion of one circumference or twice that; but one should ask pupils to estimate roughly how much the rod expands, and one should ask them how they can tell whether they have heated it as hot as boiling water or hotter. (Do not tell them that the answer is to try a drop of water on the rod. Research in science does not consist of being told the answers, and now and again we should leave a question like that unanswered so that the pupil who does think of an answer can have a full reward in his own mind.)

Experiments show that different metals expand by different amounts when heated through the same temperature difference. Explain that a copper rod expands more than the same length of iron does – about 1.5 times as much. Ask what would happen to a bar made up of a strip of copper welded firmly to a strip of iron of the same length and heated.

Ask how such a 'bimetal strip' might be used as a heat-operated switch. To what uses might such a switch be put? Whilst compensated pendulums and balance wheels are interesting, we can safely omit these applications in an age when radio time signals make cheap clocks suffice even for navigation.

125a Demonstration
Cracking glass

APPARATUS

1 Piece of window glass (about 10 cm square)
1 Tripod
1 Bunsen burner
Safety screens

PROCEDURE

Place the pane of glass on the tripod and heat one corner with the Bunsen flame. 'Why does the glass crack?'

Safety screens Whenever the teacher has to give a demonstration with something made of glass which might shatter and hurt him or the class, it is recommended that a pair of large safety sheets of Perspex be used. The sheet between the teacher and the apparatus should be 90 cm high by 60 cm wide. This is not so wide that he cannot reach his arms round from behind and manipulate the apparatus, but it is high enough to shield his face. The sheet between the apparatus and the class should be 75 cm square.

These sheets (of 5-mm Perspex) should on no account be framed for that would spoil the feeling of full transparency. They could well be supported by pairs of slotted bases (item 30).

125b Class Experiment
Cracking glass

APPARATUS *item no.*

32 7- or 8-cm lengths of soft glass tubing *57S*
32 7- or 8-cm lengths of Pyrex glass tubing *57T*
16 Bunsen burners *508*
16 Beakers *512/2*
2 7- or 8-cm lengths of clear silica tubing *57U*

PROCEDURE

Give pupils small pieces of soft glass tubing to heat in a flame and plunge in water. Then give pieces of Pyrex. If possible have a demonstration piece of transparent pure silica tubing. Ask them how they can 'explain' the different behaviour of the Pyrex. (The different behaviour of Pyrex might be due to lower expansion, ability to stand a greater strain – strain is the important quality here, not stress – or greater thermal conductivity. The first one is the real reason. The second one can be ruled out by bending glass tubes till they break: put two tubes of equal size as a bridge across between two stools. The tubes should be about 1 m long, one tube of Pyrex, the other soft glass. Push the centre of both down until they break. Usually they break at about the same bending. The question of conductivity can be investigated later when pupils try tubes of both kinds of glass in a flame and run their fingers – or an unlit match – along to make comparison of conductivities.)

Expansion of liquids

Give pupils a thermometer and ask them to dip it suddenly in hot water and watch it. Ask what they can squeeze, like a detective, out of the clues that they observe.

We suggest this analogy with the work of a detective as a very useful way of giving young pupils a picture of the work of scientists, but each teacher will need to modify the wording to fit the interests of his group of pupils.

126 Class Experiment
Mercury expanding

APPARATUS *item no.*

16 Thermometers (−10 to 110 °C) *542*
8 Aluminium containers or beakers *76*

PROCEDURE

The pupils should be asked to dip their thermometers into hot water and to watch carefully. It is possible that some may observe the initial contraction before expansion, but teachers should not mention this unless pupils do.

127 Class Experiment
Model of a thermometer

APPARATUS *item no.*

32 Soft glass test-tubes *545*
32 Pyrex glass test-tubes *546*
32 Bungs with capillary tubing to fit test-tubes *547*
8 Aluminium containers for hot water *76*

A suitable size for these tubes would be 75 mm × 12 mm.

Each pupil should have his own test-tube, but they can share the hot water baths.

PROCEDURE

Give the pupils a small soft glass test-tube corked up with a glass tube through the cork that is either a capillary tube (bore about 1 mm) or an ordinary tube drawn out to a coarse capillary outside the cork. Ask them to fill this 'giant thermometer' with water (which may be coloured) and then plunge it into a saucepan of hot water, watching what happens. They should sketch this in their notebooks and write a note of what they see. Some will only see the general expansion of the cold water in the test-tube, but some will also notice the initial dip downward. Ask what information, knowledge, and ideas can be squeezed out of that. Do not give the answer but encourage thinking and leave this unanswered. If necessary, give the answer the following week.

Then offer the same device made with a Pyrex test-tube, telling pupils that this is made of a different glass. Again, ask pupils what they can extract from what they see.

If the initial dip down is not clearly visible, either the test-tube has not been properly filled and has air bubbles, or a finer capillary is needed. If the soft glass tube does not give a much greater dip than the Pyrex tube, that tube is not made of ordinary soda-glass but has probably been supplied in some 'semi-Pyrex' – which will lead to fewer complaints of breakage but will not do well in this experiment.

Melting and boiling

Pupils should do some experiments on melting. These should be qualitative rather than quantitative; a series of measurements of temperature for a cooling curve will take more time than we ought to spend at this stage. And the pupils are not ready for it.

128 Class Experiment
Melting

APPARATUS *item no.*
16 Test-tubes (Pyrex) *546*
16 Test-tube holders *526*
16 Bunsen burners *508*
16 Tripods *511*
16 Beakers (400 cm³) *512/2*
Naphthalene
Lead
Solder (not cored)
16 Heat-resistant mats *509*
16 Pairs of tongs
16 15-cm lengths of iron wire
16 15-cm lengths of copper wire
Snow (if available)
16 Thermometers (−10 to 110 °C) *542*
Small polythene bags
1 CO_2 cylinder *19/1*
1 Dry ice attachment *19/2*

PROCEDURE

a. A little naphthalene is put into each test-tube, to a depth of between 2 and 3 cm. The test-tube is held in a test-tube holder and heated by dipping the end in hot water contained in a beaker.

b. If they did not do the experiment in Year 1, pupils should also try heating a few grams of lead in a tin lid or crucible, heating a few centimetres of solder (*not* cored) held in tongs over a heat-resistant mat, heating pieces of iron wire and pieces of copper wire in a Bunsen flame.

c. If snow is available, a melting experiment should be carried out with snow. Good results are unlikely unless the snow is very fine. Crushed or shaved ice will not do – small icebergs spoil the simple story.

Heat a 400-cm³ beaker, crammed with snow, over a *small* Bunsen flame that is kept burning at a steady rate. Hold the Bunsen under the container of snow for only $\frac{1}{4}$ minute at a time. After each $\frac{1}{4}$ minute 'dose' of heat, move the Bunsen away (but keep it burning) and stir carefully until the temperature stops changing. Then give another dose of heat. Continue thus, dose after dose, until the temperature is 30 °C or higher.

d. Give each pupil a small piece of solid carbon dioxide. They should watch it change its state as it warms up in the room. They should not be allowed to handle it with their bare hands. They should put a small piece in a polythene bag with the air squashed out and seal the bag, so that they can see the bag expanding as the CO_2 evaporates.

NOTE

The carbon dioxide 'snow' is prepared by opening the valve of the cylinder so that the gas escapes into a bag of closely woven material held over the jet of the dry ice attachment. A 5- or 10-second 'burst' is sufficient: the solid CO_2 can be peeled off the inside of the bag. It may be necessary to invert the cylinder if it is the type without a siphon tube. The CO_2 in the cylinder is liquid at room temperature and it is latent heat of vaporization that is responsible for the cooling to freeze a little to solid.

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129 Class Experiment
Boiling

APPARATUS *item no.*
16 Pyrex beakers (400 cm³) *512/2*
16 Bunsen burners *508*
16 Tripods *511*

PROCEDURE

The pupils should half-fill the beaker with water and then bring it gently to the boil. They should watch the process carefully, observing the formation of bubbles.

Changes of volume

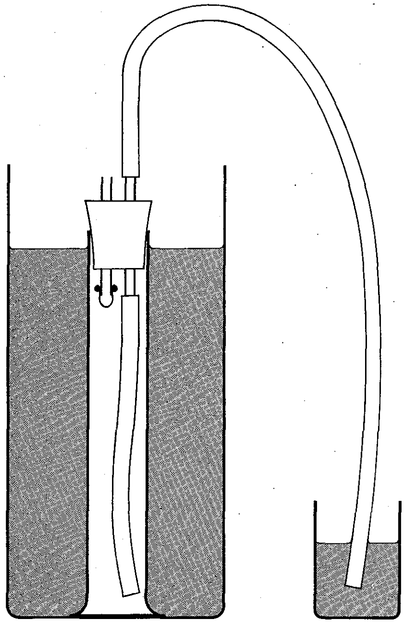
When a little carbon dioxide snow is turned to gas inside a balloon (Experiment 128) a small volume of the snow becomes a relatively large volume of the gas.

130 Demonstration
Change of volume: petrol to petrol vapour

APPARATUS *item no.*
1 Measuring cylinder (Pyrex) 100 cm³ capacity
1 Bung to fit this cylinder carrying two short glass tubes
1 2000 cm³ tall-form beaker
Plastic tubing
1 Hypodermic syringe *148/3*
1 Rubber cap *148/2*
1 Beaker (400 cm³) *512/2*

PROCEDURE

The sketch shows how the equipment is assembled. The measuring cylinder is filled with water, as is the flexible tube which leads through the bung to the reservoir. The second glass tube through the bung is closed with a rubber cap on the inside of the bung. The whole cylinder is immersed in hot water (about 90 °C) in the tall-form beaker.



About 0.1 cm^3 of petrol is then injected into the cylinder through the rubber cap tube. It will evaporate and occupy some 80 cm^3.

As the water cools, the vapour will condense again and the expelled water will return to the cylinder. This is an expansion of about 800 times; when water turns to steam the expansion is even greater – about 1200 times.

The volume change from ice to water should also be given: 1 kg of water occupies practically 1000 cm^3 (0.001 m^3) but when it freezes to form ice it swells up to a volume about 10 per cent bigger – to about 1100 cm^3.

Expansion of gases: qualitative study

Pupils should try a simple *qualitative* demonstration of expansion of gases. In a later year, pupils will meet a more formal experiment in which measurements of temperature and volume are made and the question of absolute temperature is discussed.

131 Class Experiment

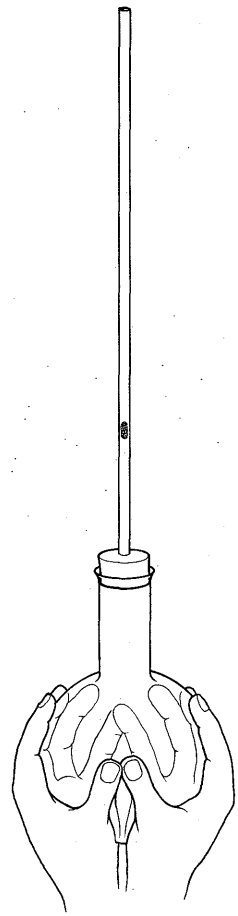
Warming up a gas

APPARATUS *item no.*

8 Round-bottomed flasks (250 cm^3) *548*
8 Bungs with narrow-bore tubing to fit *549/1*

PROCEDURE

The air is entrapped in the flask with a small bead of oil in the glass tubing.



Gentle heating with the hand will produce a sufficient temperature rise for the oil index to move up the tubing. Then the pupils should try plunging the flask first into cold and then into warm (not hot) water.

NOTE

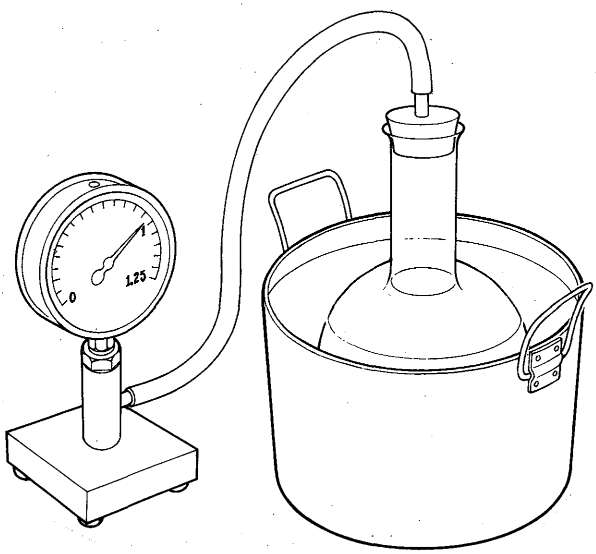
In place of the flasks, glass test-tubes and corks with capillary tubing, as used in Experiment 127, could be used here.

132 Class Experiment

The effect of warming up a gas on its pressure

APPARATUS *item no.*

8 Bourdon gauges *67*
8 250-cm³ round-bottomed flasks *548*
8 Rubber bungs and tubing *549/2*
8 Aluminium containers *76*
8 Tripods *511*
8 Bunsen burners *508*



PROCEDURE

The flask is connected to the Bourdon gauge (which should be graduated to show absolute pressure, including zero) and is then plunged into cold water (preferably at or near freezing point) and then into hot water (preferably near boiling point).

Summary of thermal expansions Pupils should emerge from these simple, directed class experiments knowing that metals expand a very little when heated, that liquids expand a little when heated, that gases expand a great deal when heated, if they are allowed to do so, but will increase in pressure if they are not allowed to expand. These experiments are for the sake of acquaintance, for what the pupil feels in his bones he knows about Nature, after having tried the experiments. Records in notebooks should be very brief indeed and measurements should wait for a later occasion.

ATOMIC AND MOLECULAR PICTURE OF MATTER

Solids, liquids, and gases

We now have an opportunity for a very important description, our 'atomic' picture of solids, liquids and gases.

Solids In discussion with pupils, look back at the discussion of solids and crystals in Year 1. Point out that we picture solids as made up of atoms in regular piling like oranges on a fruit stall – different patterns of piling for different types of crystal, the pattern being probably controlled by the external electrical properties of atoms which control their chemistry.

In solids, then, the atoms, or groups of atoms, are arranged in a regular lattice. But what happens when we heat a solid? It stays solid; so the atoms stay in their regular arrangement and yet we have tried to give them some motion. So we picture the atoms as moving to and fro, vibrating around their standard position. Thus we have a picture of a solid as an array of atoms linked by spring forces like a vast three-dimensional bedspring. The atoms are in constant vibration which grows more violent when we make the solid hotter.

As we heat a solid and its atoms vibrate more and more, we can think of them in their more violent vibrations stretching some of the springs which connect atom to atom. These springs are in fact the springs of electrical forces, the kind of forces that make two light balls with unlike charges attract, and two with like charges repel, each other. However, the vibrations can only take on extra energy in definite chunks – and there we are meeting quantum behaviour.

If pupils ask how far you can cool a solid, we might be tempted to say simply that we could cool it all the way down to absolute zero, and that then the vibrations would have stopped. But, we now have good reason to believe that even at absolute zero the atoms of a solid would be left with a small residual vibration. That is one of the curious things which the whole body of knowledge summed up in quantum mechanics makes us hold as highly probable.

Melting Heating a solid still hotter brings it to the point where the springy forces connecting atoms are, so to speak, stretched beyond their strength and the solid pattern comes to pieces. First a few atoms break loose and then all of them, moving about close to neighbours but with random motions. This process of melting, involving the tearing apart and breaking, in a sense, of inter-atomic springs, takes some energy, which afterwards lies concealed in the 'stretched springs' (force fields) that are left attached to the separated atoms or molecules. So we should not be surprised to find that melting takes in quite a lot of heat and keeps it in concealed storage. In return, when a liquid solidifies, quite a lot of heat is given out. We mention the warm air after snow forms; and the long time of heating needed to melt some ice.

Mention the storage of heat in melted crystals in some modern schemes for heating houses by stored sunlight. Pupils may do a class experiment, to feel this effect, by repeating the experiment with hypo suggested in Year 1. The teacher should prepare, the day before the class, test-tubes of melted hypo which has cooled back to room temperature but has failed to crystallize. Each pupil has a tube and adds a seeding crystal of hypo. (To prepare the tubes, place 1 or 2 cm^3 of hypo crystals in each, add one drop of water or less, hold the tube in boiling water till the crystals melt, allow to cool slowly. Protect from dust.)

Liquids In a liquid we picture the molecules as only a little farther apart than in a solid; the essential difference is that they move fast enough to keep moving in and out among neighbours so that the crowd stays fluid. Picture the atoms in liquid as moving fast and bouncing against each other, very often moving only a very short distance between one collision and the next. When one atom bounces up to a neighbour, it bounces quickly away again and does not spend a long enough time in close approach to get locked into a crystal array. Heating the liquid increases molecular speeds.

Even when viewed in the light of much fuller knowledge of physics, liquids are harder to picture and understand than gases – whose molecules are far apart and independent – and solids with such orderly arrangement. Liquids with their patches of short-range order, subject to a complex of co-operative vibrations, *are* difficult to deal with. So if pupils find the picture of them less clear we can only agree.

Gases In gases, the atoms or molecules are much farther apart so that much of their time is spent in moving fast far away from any other molecules, out of the influence of any other molecule. There are violent collisions but these occupy a very short time when strong repulsive forces come into play at very close approach. Heating a gas increases the speed of random motion.

Models: demonstrations and class experiment These pictures of solid, liquid, and gas can be illustrated: a 'solid' array of balls connected together by springs, arranged so that the balls can vibrate with various motions with some independence between one ball and its neighbours; a two-dimensional 'liquid' of many marbles crowded into a rectangular tray kept in a state of agitation; a two-dimensional 'gas' of much fewer marbles in a tray kept in motion by agitating the tray.

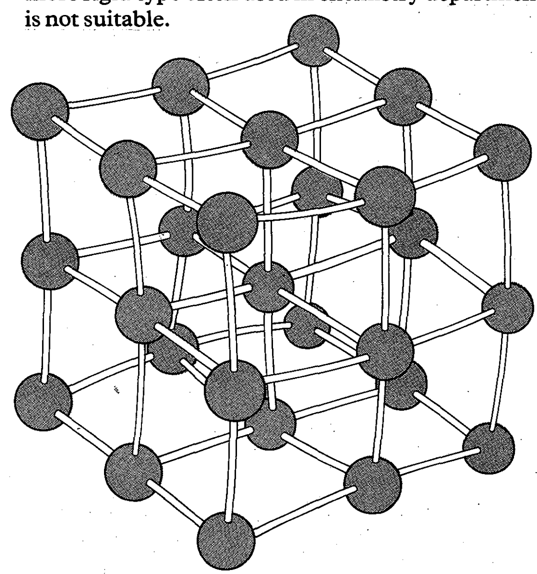
There should also be a demonstration of a three-dimensional model of gas molecules in motion. This may be a handful of plastic beads or metal balls kept in motion by a vibrating piston at the bottom of a tall wide tube of glass or Perspex.

These models, which may seem to us merely pretty toys, serve the very important purpose with young pupils of showing them our pictures of molecules which we already have clearly in our heads but which to them are quite new things that need models for teaching.

133 Demonstration
Model of a solid

APPARATUS		*item no.*
1	Atom model	*22*

The model recommended is large and 'wobbly': the more rigid type often used in chemistry departments is not suitable.



PROCEDURE

The vibrations of the 'atoms' are immediately apparent with this model though the structure retains its basic shape.

At 'higher temperature', the vibrations keep much the same frequency, but amplitudes are larger.

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134 Class Experiment
Model for evaporation of a liquid

APPARATUS *item no.*

1 Two-dimensional kinetic model kit *12*

The kit contains 16 metal trays enabling pupils to work in pairs.

PROCEDURE

Repeat Experiment 123, to simulate a kinetic model of a gas.

For a model of a liquid, more marbles are added. The tray is inclined slightly and shaken. More marbles will be necessary if each pair is to have their own liquid model. If they are not available the teacher will have to show this model as a demonstration.

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135 Demonstration
Three-dimensional model for a gas

APPARATUS *item no.*

1 Three-dimensional kinetic model kit *11*
1 L.T. variable voltage supply *59*
1 Retort stand, boss, and clamp *503–506*

PROCEDURE

The rubber base is fixed over the lower end of the plastic tube, which is held in a vertical position using a retort stand, boss, and clamp.

The height of the tube is adjusted so that the rubber base is a millimetre or two above the vibrating rod in its mean position.

The small phosphor-bronze ball-bearings are put inside the long tube so that they rest on the bottom. The most effective number will cover about two-thirds of the base area. The brass cap should be put over the top of the tube: it prevents balls from coming out and it cuts down the noise.

Start with a low voltage, then gradually increase it, showing the action of the balls increasing.

A cardboard disc can be put inside the tube to act as a movable lid for this 'atmosphere'. The wire holding the disc passes through the hole in the brass cap.

The disc falls to the bottom when the vibrator is switched off. When the vibrator is switched on, the disc rises again to a position where its weight is just balanced by the force due to the pressure of the 'atmosphere' up there. Various small cardboard weights can be added on top of the disc.

Note on models We should show models, preferably in several forms, but we should also murmur gentle warnings that a model is not the real thing, in many cases not even meant to show what we think the real thing is like. This kind of reservation is discouraging when young people first meet it; but they can learn to enjoy devising models and thinking in terms of them with much greater freedom and skill and imagination once they realize the greater scope of scientific models as we use them. We have models of gas molecules – as real balls, or in imagination – to help our thinking about gases, to suggest a line of investigation, or to illustrate a technical term such as mean free path. We might contrast such molecular models with mock-up models such as a tiny wooden model of a fission reactor or a huge wax model of a flower. The latter models are used to aid people in visualizing; the former are used for constructive thinking.

All our theoretical physics uses models as essential parts of the framework of knowledge – but with great care to remember where the words, phrases, descriptions, are only parts of models. Without imaginative thinking in terms of models, scientific knowledge would be merely a pile of facts, codified here and there in laws – little more than a handbook of data.

We cannot put this to our young pupils at this stage; and we should not even be wise to try; but we should think about our own picture of science and the part played by models in it when we use demonstration models as part of our teaching skill.

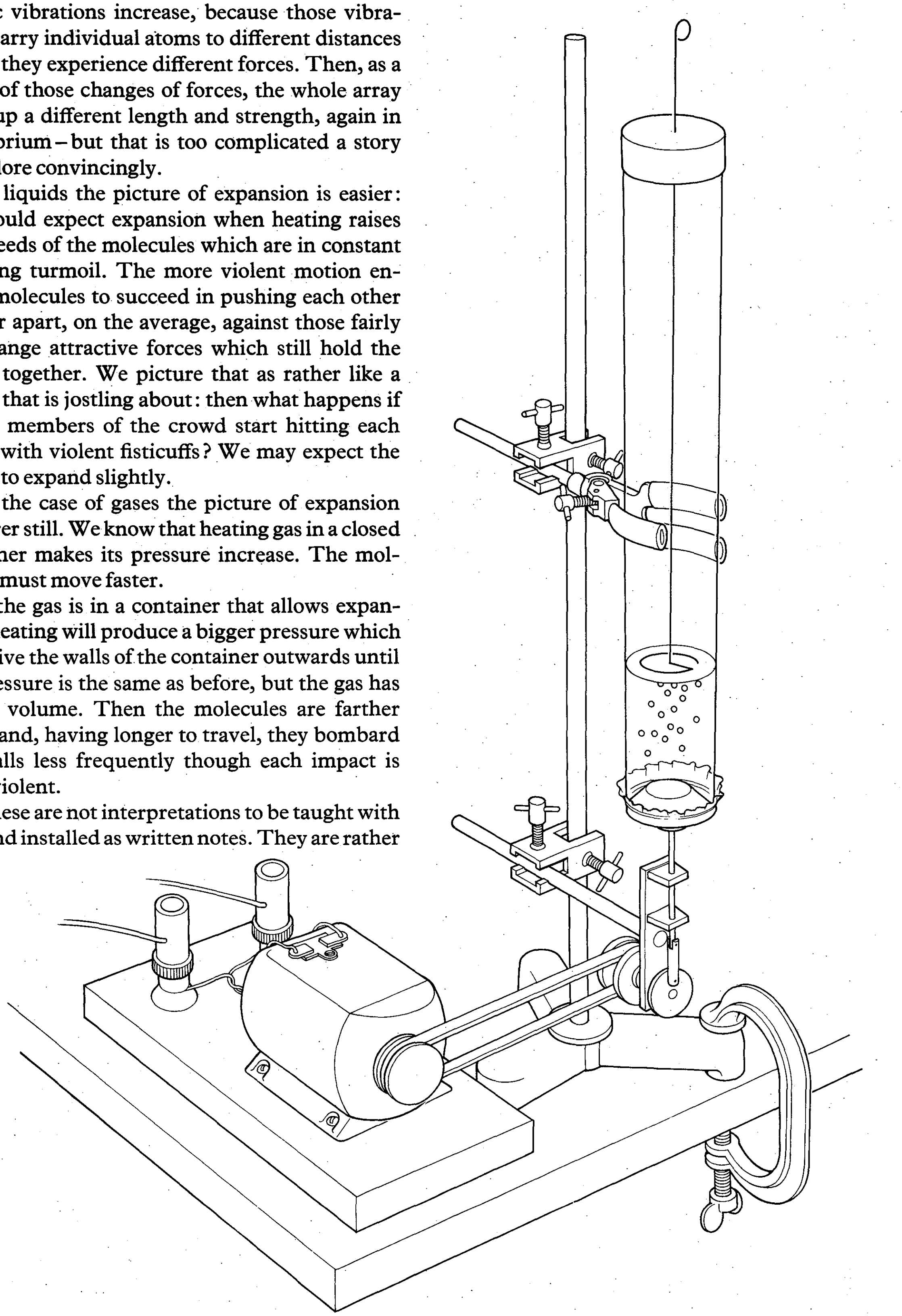
Expansion: 'atomic and molecular story' Thinking in terms of these models, we can talk about expansion of materials; we can picture the atoms in a solid metal, elbowing each other a little further apart as they vibrate more and more. A more honest picture would go into details of the competition between fairly short-range attractive forces between atoms and very short-range repulsive forces between atoms. These must maintain a system in equilibrium, changing their values when atomic vibrations increase, because those vibrations carry individual atoms to different distances where they experience different forces. Then, as a result of those changes of forces, the whole array takes up a different length and strength, again in equilibrium – but that is too complicated a story to explore convincingly.

In liquids the picture of expansion is easier: we should expect expansion when heating raises the speeds of the molecules which are in constant colliding turmoil. The more violent motion enables molecules to succeed in pushing each other further apart, on the average, against those fairly long-range attractive forces which still hold the liquid together. We picture that as rather like a crowd that is jostling about: then what happens if all the members of the crowd start hitting each other, with violent fisticuffs? We may expect the crowd to expand slightly.

In the case of gases the picture of expansion is clearer still. We know that heating gas in a closed container makes its pressure increase. The molecules must move faster.

If the gas is in a container that allows expansion, heating will produce a bigger pressure which will drive the walls of the container outwards until the pressure is the same as before, but the gas has bigger volume. Then the molecules are farther apart, and, having longer to travel, they bombard the walls less frequently though each impact is more violent.

These are not interpretations to be taught with care and installed as written notes. They are rather matters in which the teacher should talk as a senior physicist to his pupils as younger physicists.



CHAPTER 15
Heat transfer

Transferring heat through solids, liquids, gases, and across space

The year ends with class experiments to look at convection, conduction, and radiation. These experiments have clear instructions like a cookery book, but leave the children on their own in drawing conclusions: 'You are the detective. Look for clues in the experiments you do, and see what you can extract from the clues you find.' That is an attitude to science which we put now in an informal way; but one we shall use through the years.

We have talked about the 'flow of electric currents' as being rather like the flow of water. When we find the similarities in our experiments we start using the name 'current' in electricity. We also find that heat seems to 'flow' along a bar of solid and in other media, when it is *conducted.*

Heat can also be carried by wholesale movement: warmer fluid moves, displacing colder fluid and thus conveying heat in convection currents. Since pupils have been interpreting heat as molecular motion, this may be a suitable moment for some simple class experiments on heat flow (or heat transfer); and then on radiation.

Conduction, convection, radiation

Professional scientists use the words *conduction* and *convection* with confidence and pleasure in discussing design of experiments and in commenting on events in the household or in the world at large. The other words for ways of losing heat – *radiation* and *evaporation* – serve as equally useful, important pieces of language. Yet when we teach young pupils about heat transfer, the names are apt to seem more important than the real process. Freud once said: 'Words and magic were, in the beginning, one and the same thing.' Even when pupils understand very well what is happening they still regard these matters as rather a remote part of science. The danger is illustrated by a pupil's remark about a problem on a car smash: 'Oh, the force comes out at about 20 tons-weight; but of course that isn't real force, that's just an answer.'

Good demonstrations, though they are as delightful to pupils as to us, do not seem to remove the difficulty completely: the phenomena, or rather the descriptions of them, remain artificial. That can be cured if pupils do experiments themselves. We know that is necessary in the case of electric circuits, which we still think of as artificial; and we should realize that to young people heat transfer may seem equally artificial. So we offer a series of class experiments. The instructions for these will be fairly complete and clear; but that will not make the experiments completely 'cookery book' ones, because we shall ask pupils to try to argue out some scientific knowledge from the clues they obtain.

We start by telling pupils we want them to look at various ways in which heat travels from one place to another; and we describe some possible mechanisms and give our names for them – rather like Ohm having the name for resistance before he went to look for it in electric circuits.

We describe conduction as some process of handing heat on from one bit of stuff to the next, like a message being handed along a line of pupils from neighbour to neighbour. And we describe convection as a wholesale motion, chunks of material moving and carrying heat with them, like a group of pupils carrying a petition with them through a crowd. It may be best to leave radiation until after some experiments on convection and conduction; but, from the first mention of radiation, we should always say clearly:

This is quite different; it is not a matter of something hot carrying heat itself, or of atoms handing heat on from one to the next. This seems to act in quite a different way.

Hot things can and do give out radiation, they produce something at the expense of heat, so they cool down unless we keep on supplying heat to them. But the heat that disappears does not travel out as such: it seems to change and travel in an entirely different way. You will find that it travels extremely fast, and usually in straight lines. That is why people call it radiation: that means something that travels out like the spokes of a wheel, radii. When radiation hits something and stops, it usually turns its energy back into heat.

I write a message on a piece of paper. I want to get it to someone over there. That message can be *conducted* from pupil to pupil, or *conveyed* by a gang of pupils running with it. Now if we want to think about the message being 'radiated' we must take it to a radio station where it can be changed to a radio message which radiates out. On the other side of the Channel or elsewhere far away it can be turned back into another message on a piece of paper–but none of you would expect to see a piece of paper whizzing along with its message in a radio wave.

We should insist – in the early stages chiefly by avoiding misleading remarks – on regarding radiation as a quite different form of energy in motion.

Perhaps some of the difficulties which many people feel about this come from the use of the very misleading expression 'heat radiation'. *Any* form of radiation, be it green light or infra-red radiation or X-rays or radio waves, will yield 4 kJ of heat per second to any absorbing surface that is receiving a 4-kW stream of that radiation. It is true that while it is easy to make a gas fire or an electric heater, or even an ordinary coal fire emit 4 kW of infra-red radiation, it would be difficult to build any of those to emit a 4-kW stream of green light; and hopelessly difficult, and dangerous, to build a heater to emit 4 kW of X-rays. All the ordinary incandescent sources we know, including the Sun, emit infra-red radiation in a much more powerful stream than visible light. The reason why a thermopile or thermistor exploring through the spectrum is heated so much more in the infra-red is not that infra-red consists of 'heat radiation' but simply because there is more of it!

The old nursery riddle, 'Why do white sheep give more wool than black sheep?' is useful here. One watt of green light gives just as much heating, when absorbed, as 1 watt of infra-red 'light'. (We might make a small reservation in the case of X-rays since they excite some of the absorber's atoms, so that a little of the energy goes into electric fields instead of thermal motion.)

Radiation so easily develops a confused reputation that it seems wiser to be dogmatic and insist that there is no special kind of 'heat radiation' or 'heat rays'. Another peculiarity of radiation that we should establish early – and this can be done by experiment – is that it *produces heat only when absorbed*: it provides no heat as it travels through a transparent medium and it produces no heat at a perfectly reflecting mirror. It would be easy enough for us to say, 'Oh well, of course when it goes through it continues with its energy, and when it is reflected it carries its energy away with it'; but in a way that argument assumes what we are trying to explain, by imputing to radiation, just the right energy-carrying nature to support our story.

Class experiments on conduction and convection

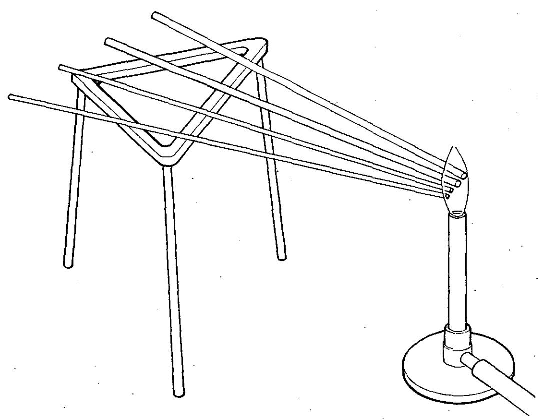
136a Class Experiment
Testing conductivities

Ask the pupils to touch a number of different materials in the room and ask them to classify them as either materials that feel cool to the touch or materials that feel warm to the touch. Unless sunlight is falling directly upon them or they are near to some other source of heat, all the materials are likely to be at the same temperature – and that temperature will be lower than the temperature of the body. So the pupils are developing a crude list of good and bad conductors.

136b Class Experiment
Comparing conductivities

APPARATUS *item no.*
1 Conductivity kit *56*
8 Bunsen burners *508*
8 Tripods *511*

The kit includes 8 rods each (25 cm long, 4 mm diameter) of copper, brass, aluminium, iron and glass (Pyrex) and 8 rods each (25 cm long, 2 mm diameter) of copper, brass, and iron.



PROCEDURE

Give pupils a Bunsen burner and a tripod stand (and a heat-resistant sheet to protect the table) and a collection of rods and wires of copper, brass, iron, glass, and other materials if possible. Ask them to make a very rough comparison of conducting powers, by placing several different rods on the tripod as support, so that each rod has one end in the Bunsen flame.

DISCUSSION

Run your finger along the rod from the outer end until you find the place where the rod is too hot to touch. See how far from the flame that place is. How does that tell you which rod is best at conducting heat?

What is really happening is that heat is flowing along in the rod rather like water in a pipe but it is also escaping from the surface of the rod so after a time the rod reaches a steady state, very hot in the flame, hot some way out, fairly hot still farther out, and quite cool perhaps at the end. Can you judge with your finger which is the best conductor and which is the poorest?

You might think it would be best to time the speed at which the heat seems to run along the rod, with a clock. But we know from further work on conduction the speed at which the heated region spreads along the rod after you put it in the flame does not just depend on the conductivity; it also depends on how greedy that particular metal is for heat, how much heat it has to receive and mop up before it grows much hotter. So the metal's 'specific heat capacity' affects the speed as well. Therefore you should go on heating the rods till they reach a steady state.‡

If you don't like using your finger, try using a match-head instead.

Also see what the thinner rods do compared with the thicker ones.

When pupils find that thinner rods do not get hot so far along from the flame, ask:

Can you think of a commonsense reason for that? Remember people say conduction of heat along a rod is rather like water flowing along a pipe.

(*Note:* we should not push this story very far: the close analogue would be a pipe that has leaks all over it!)

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‡ Young experimenters naturally want to take the *speed* at which the initial heating travels along the rod as a measure of its 'conductivity'. Unfortunately, that does not agree with our professional definition of conductivity in terms of heat flow and temperature gradient. The speed at which a particular temperature (such as the melting point of wax) travels along a bar when we start heating one end is, essentially, the speed of 'temperature waves', which involves specific heat capacity and density as well as conductivity. Thus, a rod of lead makes a quick start in the race although it is a poor conductor, but the wax-melting will not have travelled far when a steady state is attained.

The simple experiments suggested here involve heat losses from the surface of the rod. If, for steady state, the distance from heated end to melting point of wax is twice as great for rod A as for rod B, then rod A has only half the temperature gradient but has twice the surface area for losing heat (in regions with that temperature range). So we argue that A must have four times the conductivity of B.

This is a chance for young pupils to enjoy finding out about conduction. Some of them will do other things: e.g. they will melt the glass rods and try to stick copper wires in them; but that is all part of playing with thermal properties. This is not the time for any attempt at measurements, let alone difficult arguments about a cross-section and surface losses. It is just a time to see and feel things, and enjoy gaining knowledge oneself.

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137 Class Experiment
Convection

APPARATUS *item no.*

16 Beakers ($600\ cm^3$) *512/3*
16 Tripods *511*
16 Bunsen burners *508*
16 Test-tubes (Pyrex) *546*
Crystals of potassium permanganate
Sawdust

PROCEDURE

The pupils should begin by filling the beaker with water, then put one or two crystals of the permanganate on the bottom of the beaker.

The water is then *gently* heated over the Bunsen burner and the motion of the dye observed. For clear effect, use a small flame and no gauze between Bunsen and beaker (Pyrex beakers *do* stand this).

The experiment should also be tried in a test-tube. Repetitions of the experiment should always start with a new lot of cold water.

When pupils proceed to boil the water, the motion is more clearly displayed with the sawdust.

COMMENT

As the water approaches the boiling point, the pupils will be repeating Experiment 129. We should not discourage this. In fact, if this is done carefully enough, and the formation of steam bubbles is watched, the teacher too may get considerable enjoyment and even arrive at some puzzling thoughts. In making this comment, we are offering teachers a general reminder: we should be wise to let young pupils pursue what seems to them interesting developments. What we know to be sidelines, with obvious or unprofitable outcomes may seem just as wonderful to pupils as our main objective. And, since science itself has grown like that, we should allow such explorations. We should not direct the work straight back to the essential outcomes that we hope for. Of course, a wise teacher will bring it back in time; though a very wise one may leave some pupils to pursue a sideline for a very long time.

Notebooks Experiments 136 and 137 above should be mostly experimenting. The notes to be taken should consist of a rough sketch – a very careful drawing would not contain much more information – and a few words saying what happened, just like a researcher's record. This work should be doing, not writing. In the next experiment we give very detailed instructions (which certainly need not be copied into notebooks) but we ask pupils to record in their notebooks what they see happen and then to try to write down something that they conclude, some things that they can squeeze out of their experimental observations.

Your experiment will give you some clues. You should then try to say 'From that, my dear Watson . . . '.

138 Class Experiment
Convection in a test-tube

APPARATUS *item no.*

32 Test-tubes (Pyrex) *546*
32 Bunsen burners *508*
Potassium permanganate crystals

PROCEDURE

Pupils follow these instructions:

* * * * *

Put some cold water in a Pyrex test-tube. To mark any currents in the water, drop a crystal of 'dye' into the water and let it fall to the bottom without stirring. (Or you can use some water with sawdust already in it.) The dye will leave little colour as it falls; but if there are any circulating currents, it will colour the stream of water and show them.

Try two experiments, in each case holding the test-tube *with your bare fingers* at one end and warming the test-tube with a Bunsen flame at the other end.

a. Hold the test-tube near the top of the water but not above the water level. Heat with the Bunsen flame at the bottom of the tube as long as you can hold it with your bare fingers. Then use a test-tube holder or a piece of folded paper to hold it. Watch the 'dye'.

b. Cool the tube carefully after Experiment (a) and fill it again with cold water. When the water is at rest, add a crystal of 'dye' without stirring. Hold the tube at the bottom with your bare fingers, and heat with a Bunsen flame up near the top of the tube, just below the water surface. Go on heating and watch.

In your notebook, write down in your own words what you see happening in each case and draw a small clear sketch of each of the two experiments (a) and (b). Then write down what conclusions you can possibly squeeze out of the things you saw. Can you tell anything about convection, can you tell anything about any other matter of heat-transfer, judging from your experiments?

* * * * *

NOTE

The teacher should remember that some children, whose skin is easily burned, do not notice much pain during the original contact. Therefore, although it is very important for children to feel the temperature changes directly, the teacher should warn them to be careful not to hold the tube when it feels too hot for comfort. Test-tube holders – or their equivalent made from folded pieces of paper – spoil this experiment.

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139 Demonstration
Convection in a Bunsen flame

APPARATUS *item no.*

1 Compact light source *21*
1 Bunsen burner *508*
1 Translucent screen *46/1*
1 L.T. variable voltage supply *59*

The compact light source needs 12 V and takes 8 A. It may be connected to the L.T. variable voltage supply set at 12 V.

PROCEDURE

The Bunsen is lit and put about 30 cm in front on the compact light source and a shadow is cast either on to the wall or on to the translucent screen. The pupils should look at the shadow and discuss what they see with the teacher.

This experiment may be extended so that very light flakes from solid fuel tablets ('metaldehyde') are carried through the room. Heat a length of iron rod in the flame to a temperature rather below red heat and touch a tablet of the solid fuel with it. Very light flakes are produced and these will show the existence of convection currents through the room. Teachers may find it wise to do this experiment towards the end of a lesson since the drifting flakes are somewhat persistent.

DISCUSSION

Mention convection in oceans, in hot water heating systems, in saucepans, and in ventilation. Ask whether convection in a saucepan is merely slower than stirring or quite different. Ask whether winds are convection currents.

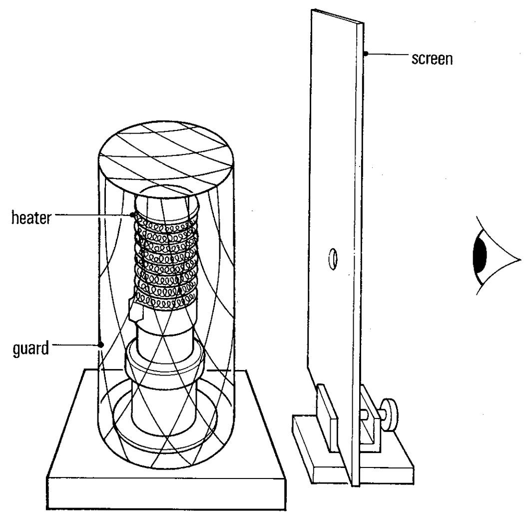
Point out that convection currents occur in gases as well as liquids: smoke will show them. Cumulus clouds show them on a grand scale in the sky; winds are convection currents.

For conduction, mention silver spoons, insulating handles, the advantage of mercury being a metal, the use of copper rod to carry heat to inaccessible places (and to carry heat from them as in the dry-ice-cooled cloud chamber). Ask about conduction through the bottom of an aluminium saucepan on a gas stove. (There is a thin, stationary layer of gas with a huge temperature difference.) Ask about clothes and air as bad conductors. Ask about house insulation (lagging, double glazing, cavity walls).

Class experiments on radiation

For these experiments, we do not use special detecting instruments such as a thermopile, but ask pupils to use their own skin's sense of warming: 'Use your cheek or the back of your hand as a detector.' For source we use a glowing electric heater (the heating element of a bowl fire), for some experiments. For others we use as source a sheet of copper about 25 cm square and 2–3 mm thick which has been heated by several Bunsen burners. One face of the sheet is painted matt black with soot in methylated spirit (*not* ordinary black paint or shiny enamel).

For a class of sixteen pairs of pupils, there should be at least four electric heaters placed around the edges of the room, and there should be one or two big sheets of copper. In front of each electric heater, there should be a heat-resistant screen, preferably covered with an aluminium sheet on the side facing the heater, with a 2-cm hole so that radiation from the heater comes straight out through the hole. It is better if the wire of the heater is shortened by about 20 per cent, so it runs at a higher temperature.



Some teachers have suggested that more heaters and other equipment should be provided to avoid long queues. But we feel that the heaters deserve some supervision by the teacher, so we do not recommend having more of them. If teachers have arranged the class in the form we suggest, a 'circus' in which pupils go to different pieces of apparatus in various orders, this amount of equipment will do well for a class of thirty-six pupils.

Cautionary notes Children should not hold their hands in front of the glowing heater for more than a second or so at a time, for some will have skin which is readily irritated by strong infra-red radiation and which may develop inflammation subsequently.

Radiant heaters used in these experiments should be enclosed in wire mesh cages so that contact, either thermal or electrical, between the pupil and the filament is not possible.

Alternative form of radiant heater If the glowing electric heaters are not available, substitute a Bunsen burner with a 'tree' from a gas fire hung in the flame of the burner by means of a handle of stout iron wire. The tree, when fully heated, will radiate very well indeed.

We may start by saying:

We are now going to look for some things that this strange thing called radiation will do. I will tell you that radiation comes out more freely from very hot things than from cold ones. It is radiation that you get from the Sun – that is another name for sunshine. Use that glowing electric heater as a source.

But since these experiments form part of a 'circus', pupils will be working on different jobs at any time. The description below therefore gives the apparatus list for each experiment together with the appropriate paragraph from the *Pupils' Text*.

140 Class Experiment
Detecting radiation

APPARATUS *item no.*

4 Heating elements *58C*
4 Heat-resistant sheets with holes *58E*
4 Slotted bases *30*

The heater is set up on the bench and connected to the a.c. mains In front of it is fixed the heat-resistant sheet held in a slotted base with the metal side towards the heater and the hole level with the element.

PROCEDURE
Pupils follow these instructions:

* * * * *

Use a glowing electric heater as a source of radiation.
a. Look through the hole in the screen in front of the heater. *Is there any red-light radiation coming through?*
b. Use the back of the hand: hold it near to the hole for a second or two. *What do you feel?*
c. Your cheek may be a more sensitive detector than your hand. Place your face about 25 cm or more away from the hole. *Can you feel any warming?* Now hold a book between the hole and your cheek. Take the book away quickly and feel what happens. Put the book back. Take it away again. Make notes of what you have found out.
d. Move your face away from the hole until you can only just feel the warming from the heater on your cheek. Ask your partner to put a book in the way but quite near to your cheek. *Does the warming stop as soon as he does that?*

Now ask him to take the book away. *When does the warming start again?*

Next ask him to put the book in the way quite near to the hole itself and then to take it away. *Does the warming stop and start immediately or is there some delay?*

Suppose the radiation which warms you travelled quite slowly. *Would the warming stop and start again at once?*

Make notes of your answers.

141a Class Experiment
Heat through glass

APPARATUS *item no.*

As for Experiment 140 together with:
4 Glass plates *58F*

PROCEDURE
Pupils follow these instructions:

* * * * *

Hold your cheek about 25 cm away from the hole in front of the heater. Hold a thick sheet of glass between the hole in the shield and your cheek. Take the glass away. Put it back. *What do you feel? What does that suggest to you?*

141b Class Experiment
Heat through glass

APPARATUS
As for Experiment 141a.

PROCEDURE
Pupils follow these instructions:

* * * * *

Now try a different version of Experiment 141a. Hold the sheet of glass beside your cheek and move closer and closer to the hole in the shield, keeping the glass between you and the heater. Then take the glass away – only for a second or two.

What does that tell you about the things glass will do with this radiation? Remember, you can see the red glow through the glass.

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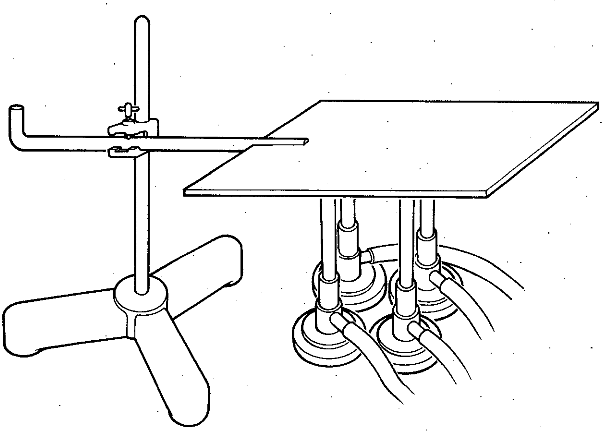
142 Class Experiment
Radiation from different surfaces

APPARATUS *item no.*

1 Copper sheet *58D*
Vegetable black *58B*
1 Retort stand and boss *503–505*
4 Bunsen burners *508*
Methylated spirits

PREPARATION

One side of the copper sheet should be given a coat of vegetable black mixed with methylated spirit and allowed to dry so that it has a dull black surface. The other side of the plate should be polished bright, though tarnishing in the flame is inevitable.



The copper sheet is secured rigidly to the retort stand, using a boss, so that the sheet is horizontal with the bright side downwards. It is then heated vigorously with four Bunsen burners underneath until it is as hot as possible.

The Bunsen burners are removed and the plate turned so that it is vertical.

PROCEDURE

Pupils should successively (and as quickly as possible), hold their cheek first near the bright side then the black side and then back near the bright side. Alternatively, they may hold the backs of their hands near the plate – one hand on either side.

The plate should be re-heated after every 6–8 pupils have tried it.

A large copper box heated by having a lot of steam blown into it will suffice as a poor substitute. A small 'Leslie cube' with boiling water in it does not give pupils a fair chance to feel the effect.

Is there any difference between the radiation that comes from a bright shiny surface and the radiation that comes from a dull one or a black one? Try to find out by holding the back of your hand near to the sides of a very hot sheet of copper. One side of the sheet is brightly polished and the other side has been blackened with soot. What does that tell you about the way radiation comes from hot surfaces?

(If pupils express doubt about the two faces being equally hot, it may be wise to 'lean over backwards' by applying the Bunsen flame to the bright side.)

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143 Class Experiment
Receiving radiation

APPARATUS *item no.*

1 Heating element *58C*
1 Heat-resistant sheet with hole *58E*
1 Slotted base *30*
Aluminium leaf *58A*
Vegetable black *58B*
1 Paint brush
1 Crystallizing dish *528*
Methylated spirit

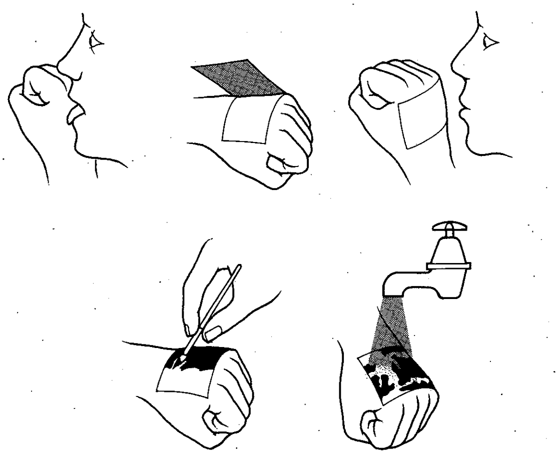
PROCEDURE

Set up the heating element with the heat-resistant sheet in front of it. A pupil should first put the back of his hand near the hole for 1 or 2 seconds (see warning above). Then the teacher covers the back of the pupil's hand with aluminium leaf and the pupil holds his hand there for 1 or 2 seconds or longer. Thirdly, the teacher coats the aluminium leaf with a vegetable black paint. When the paint is dry, the pupil again puts the back of his hand in front of the hole for 1 or 2 seconds.

NOTE ON TECHNIQUES

The teacher should have a booklet of sheets of aluminium leaf (*not* aluminium kitchen foil, but leaf, like gold leaf). When the pupil is ready to have his hand coated, the teacher should say: 'Clench your fist tight, lick the back of your hand until it is quite wet all over. Then hold it out to me.' The teacher then lays a sheet of aluminium leaf gently on top of the wet skin. He blows on it to push it on to the skin, saying, 'Relax your hand just a little to avoid cracking the aluminium leaf'. (The pupil must *not* open out his hand, or the leaf will crumple. He simply relaxes it a little.)

For black paint, to be used over the aluminium leaf, a mixture of soot and alcohol, of the consistency of thick soup, is prepared beforehand. It is applied with a large soft paint-brush about 3 cm wide. When the pupil comes back for this, the teacher applies black paint gently, saying, 'Wait till this paint is dry, then try your hand in the front of the hole'. Pupils must be instructed to WASH THE BLACK PAINT OFF UNDER A RUNNING TAP and not to try to rub it off. Rubbing will smear the soot into the skin, but a fast stream of water from the tap sweeps the soot first and then the leaf, and hands, will be fairly clean. This is a messy experiment for the teacher to administer: but it is so impressive and fruitful that those who have tried it continue to use it.



It is clear to us as physicists, even if only by habit of teaching, that a black surface absorbs radiation completely. That is not obvious to children. Even the word 'absorbs' needs to be translated into 'stops, and doesn't send it back'. We need to discuss this carefully, asking questions such as:

Suppose some white light from a lamp falls on a sheet of paper and the paper fibres reflect it, making it shine back towards you. Will you see the paper bright or dark? Suppose some green light from a special signal lamp . . . Suppose you painted the paper black instead . . . ?

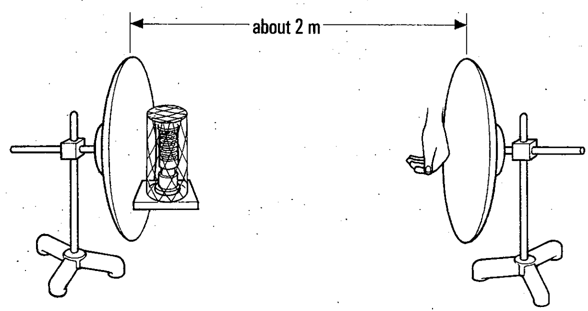
It is certainly not obvious to children that if radiation is absorbed by a black surface (or anything else) it must produce heat. In fact it is this experiment which should tell them that, and not any statement in a book or assertion by us.

Only some moving things produce heat when they are stopped: light waves, sound waves, hammers hitting lead, electrons hitting a target, X-rays stopping in dense material. Even the last two do not always turn all their energy into thermal form: an electron may produce an X-ray photon instead, and an X-ray photon may whip out a photo-electron and give it kinetic energy. We may even imagine a train of purely geometrical waves which carry no energy but are just a moving pattern that will make no heat on being stopped. (Or we may make a joke and point out that a stream of kindness warms the heart of someone who receives it but not with thermal energy.)

Extra experiments

144 Class Experiment
The reflection of radiation *(Optional)*

a. If a pair of metal-surfaced, parabolic mirrors is available, a demonstration should be set up to show that (infra-red) radiation can be reflected and focused like light. Glass mirrors fail, unless their *front* surface is coated with metal, because glass is 'black', a good absorber, for most infra-red radiation. Unfortunately, large parabolic mirrors are very expensive and we do not think the cost is justified. However, the parabolic bowls that were used until recently for electric fires with a compact heating element in the centre are available and are suitable. Two should be obtained, one of them with the heating element that is needed as source.



The two mirrors are set up at opposite ends of the bench, facing each other. A glowing electric heater is set up at the focus of one mirror and pupils are asked to try placing their hands at the focus of the other. This can even be developed into a demonstration that radiation travels very fast. A pupil holds a large sheet of wood or cardboard in front of the 'source' mirror, while another pupil holds his hand or cheek at the focus of the mirror. The obstructing wood is removed suddenly and the observer is asked to note how long it is before the warming effect reaches him. At best, this only shows that radiation travels very fast.

b. Water inside a copper box is kept boiling using an immersion heater. Alternatively the box is

kept at 100 °C by passing steam through it. One face is bright; one face is dull black having been coated with vegetable black; one face is covered with white paper pasted on. The back of the hand or the cheek is used to compare the radiation.
c. 'Try putting white paper on your hand instead of aluminium leaf. (You might expect a surprising result since your pale hand did not appear to be very different from black in receiving infra-red radiation.)'
d. Put a thermometer in a metal beaker of hot water and time the water cooling, first with a well-polished metal beaker, second with the same beaker after it has been given an 'overcoat' of soot (by painting soot and alcohol on it).
e. 'Some electric light bulbs have a vacuum in them; others have inert gas. Investigate a light bulb when it is running by feeling it with your fingers. Can you decide whether there is a vacuum or gas inside? This is an example of good scientific detective work.'
f. 'Put your cheek near an electric light bulb. Switch the lamp on and off and see whether you can feel the radiation from the lamp arriving very promptly on your face.'

General comment on radiation experiments
In a way, we beg the question all the way through these experiments by saying they are experiments on 'radiation'. Yet by the time pupils have done them, they are in a position to know something about the properties of this process or phenomenon that we call radiation, because we have collected for them experiments that illustrate some properties. Young people seldom raise the objection that they have been treated in an illogical way; and in this case we may rejoice in the knowledge they have acquired and in the experience they have gained, with a lot of help from the teacher, in extracting the concept of radiation properties from these experiments.

Spectrum demonstration

It would be a pity to leave this collection of observations and attempts at conclusions at this stage, with radiation remaining an unidentified, invisible creature. So, now, at the end of these experiments, although pupils know nothing of optics, they should share Newton's own delight on first making a spectrum.

145 Demonstration
The spectrum

APPARATUS *item no.*
1 Compact light source *21*
1 L.T. variable voltage supply *59*
1 Large positive lens *93B*
1 High-dispersion prism *69*
1 White screen *102*
1 Radiation transistor (B.P.X. 25 or equivalent)‡
1 1.5-V cell *52B*
1 Demonstration meter *70*
1 d.c. dial: 2.5–0–2.5 mA *71/4*

PROCEDURE
Set up the compact light source (which requires 8 A at 12 V). No slit is needed – the lamp filament is small enough.

Place the lens about 20 cm from the lamp (if the lens is plano-convex its plane face should be towards the lamp). Move it to make an image of the filament on the white screen some 2 to 3 m away.

Then place the prism just beyond the lens and move the screen round to catch the spectrum *at the same distance from the lens as before* but in the new direction.

The spectrum will be pure enough for this demonstration if the prism is turned to minimum deviation. To make the spectrum longer, incline the screen to the beam.

Connect the radiation transistor and cell to the demonstration milliammeter. The transistor must be shielded so that it cannot receive radiation by a direct route from the lamp and its very hot

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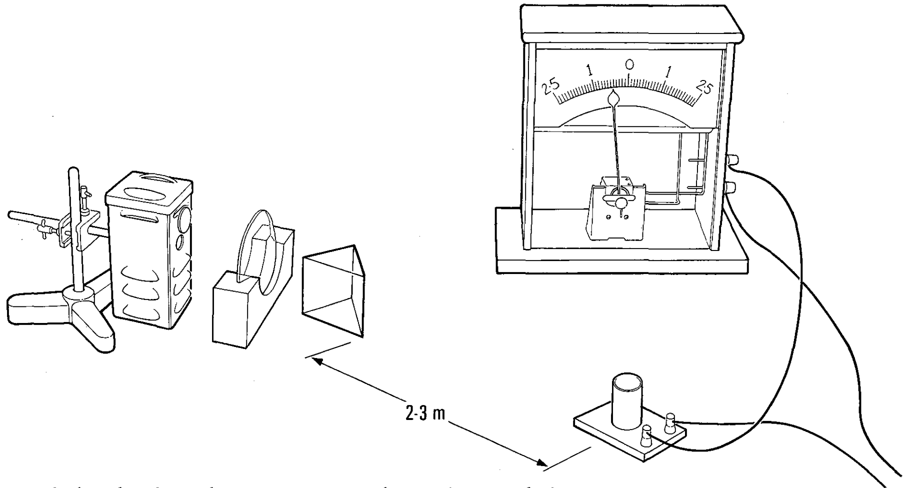
‡ The proper, 'honest' device for receiving the radiation would be one that measures the flow of energy in each part of the spectrum – by measuring a rise of temperature as the sample of radiation is absorbed. A thermopile can do that but it is itself slow or very expensive, and for a meter to exhibit readings a d.c. amplifier is needed. A bolometer designed for school use would be admirable, and a suitable one can now be obtained from Grove Industries, Grove House, Grove Road, Fareham.

Here, the use of a 'radiation' transistor is suggested. That does not measure the energy flow but responds to photons all through the visible spectrum and a short way into the infra-red. It shows increasing response from green to red and still greater in the infra-red. Then there is a sudden cut-off in the near infra-red. The cut-off is more likely to be the photon limit of the transistor than the cut-off due to glass absorption, which is always met with a thermopile or a bolometer.

The radiation transistor suggested gives a quick reading on a milliammeter, and although it would be dishonest to call it a truthful energy measurer, it tells a valuable qualitative story.

housing. Move it through the visible spectrum and out beyond to show – quickly – that energy is arriving. At this stage give no explanation beyond pointing out that the prism somehow splits up the white light into all these colours.



Ask whether there are any colours beyond the ends of the spectrum.

Well, of course, not visible ones; but are there any things arriving like these patches of coloured light beyond the ends of the spectrum?

We have been talking about radiation. We know that it comes from glowing things, that it seems to travel in straight lines, that it seems to travel very fast; and we know that light does these things. Perhaps light is a special form of radiation which our eyes happen to be able to detect. And perhaps there is radiation, to which our eyes are blind, outside the visible spectrum. Absorb (stop) the radiation and look for some heating. What should we stop it with? . . . Yes, you found that a black surface was best for that, so we take a small, very sensitive 'thermometer', paint it black, and move it along the spectrum like this.

This is, of course, a demonstration to rehearse carefully beforehand. If there are hot-water pipes or a radiator across the room in front of the device, it will truthfully record their presence in a disconcerting way. And even after a successful rehearsal, the radiation from pupil's hot faces in the audience can spoil things.

Discussions of ultra-violet light and its properties, colours and colour mixing, the extended electromagnetic spectrum, are best postponed to a later year. This demonstration is simply meant to be an exploration of the radiation-richness of various parts of the spectrum from, say, white-hot tungsten – a first look at a white-light spectrum for delight.

Index

(*continued*)

This volume contains the work for the first two years of Revised Nuffield Physics. The main titles of the chapters are for Year 1 : Materials and molecules, Weighing small things, Rough measurement, Balancing a seesaw, Investigating springs, Air pressure and molecules, Measurement of a molecule, and Energy – a first look. For Year 2 they are : About forces, Electric circuits, Electric currents, More about forces, Using energy, Warming things up, and Heat transfer.

Pupils' Text Years 1 and 2 is in parallel with this volume. There are teachers' guides and pupils' texts for each of Years 3, 4, and 5. Also for teachers is the *General Introduction* to the Revised Nuffield Physics programme.

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