REVISED

NUFFIELD PHYSICS

Teachers' Guide
Year 4

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Nuffield Physics
TEACHERS' GUIDE
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General Editors
Eric M. Rogers
E. J. Wenham

Contributors
G. E. Foxcroft
D. W. Harding
J. L. Lewis
A. W. Trotter

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NUFFIELD PHYSICS TEACHERS' GUIDE YEAR 4

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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 realise 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 *Questions 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 *Questions 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 Jim Scholefield, and their 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:

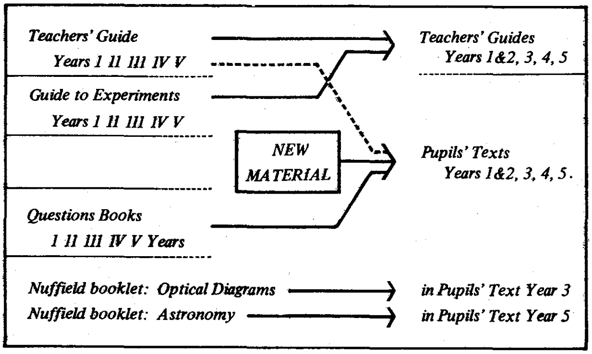
1 Let pupils work in the lab in small groups, often pairs, and leave them alone to make their own mistakes and find their own solutions, except where rescue is needed. That seems to us near to professional science.

2 Use stimulating questions as principal learning aids to encourage discussion, reasoning, and use of 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. We should not change the programme in a way that would 'lose the Nuffield spirit'. The Foundation recognised the changes in school structure but considered that other programmes, such as Nuffield Secondary Science, make better provision 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 schools 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

*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 'memorising formulae' is not so important. Candidates realise that memorising 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 reward with bonus marks.

experiments and some discussions of ideas, also thinking questions and progress questions. Thus for many pupils this text 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 concerning Physics and teaching and people; to John Maddox, Director of the Foundation, for past interest and care, and now special encouragement.

And we are grateful to Jim Scholefield who has relieved us of administrative burdens connected with the project.

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.

Producing material for these books has involved consulting, planning, editing, making preliminary sketches, trying experiments and writing chapters. All that has depended on the work of many people associated with the editorial office. In particular, the project owes a special debt to the following for loyal skilful help:

Secretaries: Elizabeth Aldwinckle, who did so much for the development of the Year 3 books, and continued, until she left for university studies, to prepare Year 4 with the same skill and understanding. Gillian Brown, Ann Sinclair and Rydal Wade continued the work and extended into some general editorial activities.

Editorial Assistants: Hilary Bunce, Mary-Jean McNeil, Jan Miller and Ron Taylor gave valuable help; Jean Richardson and Truda Temkin brought, and used, special skills.

Art Work: Mr Stanley Wood showed special understanding of our needs; Adrian Ball and Associates helped in the final stages; Lorna Jeans acted as constructive critic and courier for art work.

Physics Reader: Bill Trotter acted as physics critic and saved us from many a mistake.

Typesetting: Although outside our editorial group, Keyspools—who did the typesetting—earned our admiration for their intelligent flexibility as well as for their speed and skill.

And, in general, we are grateful to the Staff of the Nuffield Foundation, who made our work easier by many kindnesses.

All who have contributed hope that this new form of the programme will enable many of the next generation to enjoy physics and remember it all their lives.

Eric M. Rogers
E. J. Wenham
General Editors

Preface to Year 4

Year 4 is a stage for more serious and thorough study—still with enjoyment and delight, we hope, but now with more reasoning and co-ordinating thinking to give intellectual satisfaction—a Year in which pupils learn to 'make a noise like a physicist', as Rutherford once put it.

We might think of pupils in Years 1 and 2 as taking a journey in a bus across some of the foreign countryside of physics: making acquaintance with things seen from the window, exploring a town here and there in a carefree way, and learning, unconsciously, some of the vocabulary of the inhabitants. In Year 3, the boys and girls were making a more serious journey to visit a foreign family and learn how people live, to develop a vocabulary of phrases as well as words—but still rather a visit to explore and make acquaintance than an expedition for serious study. Now on their journey in Year 4, our young pupils should do much more; they should read the timetables, plan with maps, and look forward to reading the literature of the land they visit with sufficient care and appreciation to gain a sense of knowledge.

Thus, we should present the physics of Year 4 as a more logical and closely knit study than that of earlier Years. If the previous work has been satisfactory, pupils will have had sufficient experience and enjoyment to wish to undertake the work, and will continually ask questions—which at this age call for a more highly organized intellectual structure for the subject.

However, it is important that this change of treatment should not be made the excuse for a degeneration into a purely mathematical exercise: theory should be soundly related to experiment—and that experimental work should remain largely the pupil's own class experiments, and only sometimes be teachers' demonstrations to save time.

PREPARATION PROVIDED BY YEAR 3

Preparation by Year 3 is essential. It will have provided some foundation for this Year's work in dynamics and in electricity and magnetism. Pupils should now be familiar with the ideas of acceleration and velocity and their measurement. They should have some operational knowledge of inertial mass and force—but it is doubtful whether they will have a grasp of any formal version of Newton's Second Law; and although they may have seen collision experiments, the idea of momentum will not have been mentioned.

Year 3 will have built on the electric-circuit work of Year 2 by pupils' experiments with the electromagnetic kit: magnetic fields due to currents and due to permanent magnets; the motor effect; a working electric motor; electromagnetic induction and simple dynamos.

Some pupils may have done experiments with a transformer; and some fast groups may have used a voltmeter—but we should not rely on the preparation having gone as far as that.

YEAR 4 AND EXAMINATIONS

In most programmes of teaching physics in school, there is some major stress on learning new material in Year 5, because pupils are then more mature and have a well-prepared background, and face examinations. In our programme, we suggest bringing some of that attitude back from Year 5 to Year 4, where we can give some formal treatment more comfortably, without the immediate shadow of an external examination. The knowledge of physics which we have been exploring in earlier Years should now be consolidated, so that by the end of this Year pupils have some sense of physics as a connected science and are ready to explore important continuations in Year 5. For example, Year 1's introduction to ideas of atoms and molecules now links with kinetic theory of gases, and the idea of electrons with atoms of charge joins in. The introduction to energy in Years 1 and 2 now broadens into general conservation, and kinetic energy becomes a quantity that can be calculated. Pupils see how energy plays an essential part in defining voltage. 'Laws', first seen in simple examples such as Hooke's Law, now include great generalizations such as conservation of momentum and conservation of energy.

We trust Year 5 can follow its programme without pupils and teachers feeling that only then, at last, have they reached the solid examination material. We hope much of that material will have been reached already, both in matters of information and in attitude towards understanding science.

Thus we hope to avoid making Year 5 a servant of examinations, partly by the construction of the programme in earlier Years, partly by asking for examinations that require a general understanding of physics rather than factual material that can be crammed or coached in a final year.

YEAR 5 AHEAD

Year 5 will deal with electron streams crossing magnetic fields, the mass spectrograph, and experimental studies of radioactivity. Those studies will, we hope, make a good contribution to pupils' knowledge of 'atomic physics' and give many a pupil a keen interest that will carry him into further reading on his own.

In Year 5 we offer—as a section for pupils' reading—to conduct a historical study of planetary astronomy and apply Newton's Laws of Motion and of Gravitation to it, so that pupils appreciate the grand conceptual scheme which Newton himself set forth. Our aim in including that in our physics programme is not to teach astronomy but to let pupils see for themselves how good theory is developed. That will give them, we hope, a lasting feeling for the use of theory in science.

Year 5 continues the story of atom models, using a description of alpha-particle scattering to lead to a nuclear atom model. And, for pupils with keen interests, we hope to continue to other topics in modern 'atomic' physics such as wave-particle behaviour; photo-electric effect and 'photons'; and perhaps energy levels.

THE WORK OF YEAR 4

With those thrilling developments ahead in Year 5, we must consider the necessary preparations to be made in Year 4. We can make Year 4 a very interesting Year, with some of its pleasure that of growing discipline as a scientist, and a very fruitful one in preparing some material for examinations.

In Year 4 we should give pupils a good opportunity to explore Newton's Laws of Motion by their own experimenting—not to discover those laws, but to make measurements that illustrate them. Out of those measurements should come an increasing sense of 'mass' as a very important tangible property of matter—and, as pupils will find later, of energy. They should also consider Newton's Second Law in terms of momentum changes; and, with the Third Law, arrive at a clear knowledge of Conservation of Momentum.

Pupils should apply Newton's Laws of Motion to the qualitative kinetic picture of gases that we built up earlier, and arrive at a theoretical expression for gas pressure. That at once leads to a numerical prediction of the speed of molecules from simple measurements. Then there should be further discussion of kinetic theory. We shall even arrive at the size of an individual molecule, from a simple experiment and some imaginative reasoning—but that will need courage to follow a difficult line of thought, and only some pupils will appreciate it. Others should be assured that they need not remember the reasoning.

Electrical studies will continue: first with voltmeters added to circuits; then with streams of electrons in 'almost vacuum'. Then pupils meet transistors.

We discuss Millikan's great experiment which shows that there is a universal 'atomic charge'—that electrons are all alike. That needs a film at this stage and a Nuffield film is available.

The idea of putting together knowledge from several parts of physics should be emphasized when there is opportunity. This should be a Year of interesting experimenting, some reasoning, some thinking, and the building of a more solid sense of knowledge.

TEACHERS' PLANNING

Since Year 3 gives pupils informal practice with tickertape for measurement in exploring Newton's Laws of Motion, any teacher coming new to the programme with Year 4 should first look at the work of Year 3 in mechanics, and for that matter in electricity and magnetism too. And he will need to look carefully at the introduction to energy and work in Years 1 and 2, or the extra chapter on Energy at the end of *Pupils' Text 3*.

With less academic pupils, teachers will find that the burden of establishing links with the Year 3 material threatens to give them more than can be done in Year 4—unless the teacher spoils the whole point of the programme and hurries through the material by giving lectures and demonstrations and notes to be learnt. There would be nothing wrong with that condensed treatment if our aim were to cover the material for future training and for immediate examinations. However, one would not then be giving the Nuffield programme a useful trial.

So we offer teachers the following comments about speed of teaching:

The electricity and magnetism can be hurried considerably.

The kinetic theory treatment cannot be hurried; but if teachers consider the material very carefully in the light of the ability of their pupils, they will be able to plan a treatment which will not take very long—the abler pupils who deserve the whole of the discussion of molecule size, etc., will be able to take even that quite fast. All should look at Chapter 6 of *Pupils' Text 4* (chiefly for 'catching up'). All should work through Chapter 7 carefully. Then Chapter 8 will need the teacher's skill to make it a challenge and a delight.

The energy-conservation discussion in Chapter 9 on the work of Joule and others (for pupils' own reading) should not take long. However, we hope that every teacher will give that chapter serious emphasis.

The class experiments on dynamics—force, mass and motion, and momentum conservation—should be hurried gently. It would be very unwise to hurry them much, particularly as they come at the beginning of the Year, but they should not be allowed to drag.

In looking at the commentary on the timing of the programme, given above in reverse order, teachers will see that a careful, almost leisurely, start of studies of motion will be justified. And they can look forward to considerable elasticity in the later electrical work on a.c. and oscilloscopes, which can be postponed to Year 5. That would be better than any attempt to compress or economise the continuing treatment of electron streams and the description of Millikan's experiment—which comes now and forms a very important part of our physics programme.

Since the treatment in this guide for Year 4 inclines towards a more formal approach than in earlier Years, new teachers may find that a glance at the guides for Years 1 and 2 will give them a clearer idea of our underlying aims, which were set forth more fully there for teachers beginning the programme. We have the same aims in Year 4.

FORMULAE

As an example of our attitude: we are glad to see things like the following printed on the front page of Nuffield examinations, to provide information for pupils, who will then be asked to make good use of them.

$PV = \frac{1}{3}Nmv^2 \quad F = ma \quad Ft = \text{change of } mv$

and even (without explanation) the rubric 'volts = joules/coulomb'.

SHORTENED PROGRAMMES?

Some schools find they would have to shorten our programme for Years 3+4+5 to two years before they could adopt it. The following note explains the difficulties of some suggested forms of shortening and urges schools who need a two-year programme to make a fresh start in constructing one.

Even if our present programme gives little detailed help in such new planning, we believe our general guiding principle will still be fruitful: that we should *try to bring to our young pupils the spirit of our sixth-form physics teaching—the genuine doing of science and learning for understanding*.

Could a Class begin the Programme at Year 4?

It is not possible to make a good beginning as late as Year 4. We have found that it damages the programme very seriously.

In Year 4 pupils need the preparation with trolleys given in Year 3; otherwise, the work on Newton's Laws becomes too long and boring, and its extension into kinetic energy experiments does not get a fair treatment with class experiments.

Electric circuit experiments in Year 4 should follow those of Year 3; and if pupils have to go back and do the long, important, series of class experiments of Year 3, their progress now in Year 4 will indeed fall short. And if we try to save time by teaching the Year 3 preparation in electromagnetism by quick demonstrations we lose much of the point of our series of *class* experiments with the electromagnetic kit. Furthermore, the work with that kit presupposes a series of class experiments on electric circuits in Year 2; and pupils who missed those would need some extra preparation, even if they had seen some electric circuit experiments in a different programme.

Our strong treatment of kinetic theory in Year 4 draws upon acquaintance with a picture of molecules in motion in gases—and some pictures for solids and liquids too—built up in Years 1, 2 and 3. Pupils who began at Year 3 can perhaps replace the preparation of earlier years by watching several demonstrations; but pupils who started at Year 4 would find that those added to their burdens too seriously.

So we urge schools very strongly to embark on our programme only at Year 1 or Year 3; and not to start at Year 4. That does not mean that we think the content of Years $1+2+3$ is an ideal minimum programme. Doubtless, a good programme of teaching physics with the spirit and methods we suggest could be constructed to occupy two years. Such a shortened programme could hardly be made by picking parts from our present programme without losing much of its value. We have tried to make our programme a connected scheme in which some topics are introduced early and treated again with increasing sophistication from year to year. To make a similar, connected scheme to be taught in two years instead of three, it would be necessary to plan from a fresh start.

Could a Class omit Year 5? Another suggestion for a two-year course based on our programme, is that pupils should start at Year 3, proceed to Year 4, but omit Year 5. With our present structure, that would indeed present the course as a headless body. Without its uses for astronomy and for electron streams in Year 5, the work on Newtonian dynamics in Years 3 and 4 would seem much nearer to sterile drill. Without the study of light waves and interference in Year 5, the ripple tank experiments of Year 3 would seem a pleasant sideshow. And without the topics of atomic physics in Year 5 our early interest in atoms and molecules would lose a considerable amount of its value.

Of course, pupils who continue with physics and shift our Year 5 treatment into A-Level will lose nothing; and they may gain by being in a fast group that can use special mathematical tools. But others who leave physics after O-Level would miss the proper drawing together of old topics and the fruitful look at present-day physics which we feel the programme owes them in Year 5.

We hope that schools who must compress what we call Years $3+4+5$ into two years will make a fresh start in planning a new programme to fit their needs and will not try to compress our programme or upset its structure by picking items from it, while hoping the result will serve the same ends. We hope our examinations, both those in schools and those set by Boards, will continue to look for understanding—particularly in their marking. So we must warn schools who plan a two-year version taken from our present programme that their pupils are likely to find *our* examinations ill-suited.

We express these doubts from no feeling of unkindness or of false pride in our programme, but from our knowledge that we have carried out our instructions, which were to make a concerted five-year programme leading to O-Level. We do not think our programme is unique or ideal; but we do believe it is a good programme for pupils who can give it the time for which it has been planned. A shortening of time brings temptations towards quick memorizing. On the other hand, as in most teaching for understanding, a spread of time for digestion is one of our strongest aids.

USES OF NEWTONIAN MECHANICS

Before embarking on a serious study of Newton's Laws, all of us who teach might profitably reflect again on their importance and uses. The Laws are great guiding summaries, consistent with the behaviour of things in our world.* Even if they are not based fully or directly on experiment, they provide a basis for examining nature, relating one natural event with another, and predicting other

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* They are very important in modern physics—we need them in detailed studies of atoms, rockets, stars. ... But we do not now regard them as simple experimental laws: to us they are a mixture of experimental knowledge and definitions which we assume to organize our science.

The experimental basis *is* there: Newton's Laws *do* fit our world. In relativistic terms, we *do* live in a world that is approximately in inertial frame. If we had lived in a strongly accelerating frame, we might never have arrived at those laws.

events. In that role, they seemed very important laws to Newton's contemporaries and to physicists ever since, including Einstein:

> 'No one must think that Newton's great creation can be overthrown by "Relativity" or any other theory. His clear and wide ideas will forever retain their significance as the foundation on which our modern conceptions of physics have been built.'
>
> Albert Einstein (1948)

However, we cannot expect a pupil to see the importance and glory of these Laws unless he understands what they summarize, why they are drawn as summaries, and what use is made of them.

Motor cycles and railway engines can be understood more easily by common sense than by use of Newton's Laws. To understand the firing of a rocket, a *qualitative* knowledge of Newton's Laws of Motion is valuable; but the proper *quantitative* form that we deal with in Year 4 is of little use in practical mechanics until more advanced studies of rockets *with their changing mass* are undertaken.

Kinetic theory of gases makes good use of Newton's Laws, but that is still ahead of us. And we make some use of the Laws in our studies of electrons and atoms in Years 4 and 5.

Satellites are of great interest to pupils and an understanding of them does need Newton's Laws. In fact, the first plan of an artificial satellite was made by Newton himself. In his addition to later editions of the *Principia*, he sketched the Earth with a mountain on it and a gun firing projectiles from the top of the mountain. For faster and faster projectiles, the path landed further and further out until it reached an orbit that would just encircle the Earth. Newton himself pointed out the obvious difficulty of air resistance; and he did not expect artificial Earth satellites to be practicable.

Except for kinetic theory and satellites, our possible uses of the Laws lie in the future and the need for them is not very clear to pupils in Year 4. So unless we can show a more appealing need, we must not expect our pupils to be thrilled with the power that a knowledge of Newton's Laws can give them. They should study Newton's Laws rather quickly, leaving further emphasis and extension and revision until need arises.

We certainly should not crown our experimental studies and short theoretical discussion with nothing more than artificial problems constructed to test pupils' use of Newton's Laws; not even artificial problems constructed to find out whether pupils understand Newton's Laws—understanding will come later when uses and needs are clear.

If this discussion of our teaching plans seems depressing, reflect on Newton's own work. Newton gathered a good deal of knowledge of force and motion from the writings of Galileo (who himself copied much of his work from a few earlier writers who had been quietly reforming knowledge of motion). Newton applied this knowledge and his own thinking to the great problem of his day—the motion of planets. A revolution of astronomical knowledge was 'in the air'. Galileo's teaching and writing had spread the Copernican picture of the planetary system across Europe. Jupiter's moons, seen through the newly invented telescopes, even provided a model of the system. Kepler had disentangled three astounding laws of planetary motion from the observations of Tycho Brahe, and had announced them in a profusion of mystical writing. The Copernican theory was being accepted, but Kepler's Laws raised interesting questions: what kind of machinery could account for these experimental laws that described the planetary motions so well? Kepler himself had mentioned magnetic forces and even gravity spreading from the Sun, but not with any understanding of the relations of force and motion that would make a consistent story. Questions were being asked across Europe. There were suggestions of a force like gravity, emanating from the Sun and growing weaker with distance, perhaps with an inverse-square law.

Thus, in the 1660s, more than a century after Copernicus's book appeared, there was a ferment of discussion. It was clear from Galileo's writings that one need no longer look for a force to propel a planet *along* its orbit—motion continues if left alone. The problem instead was one of finding the force that pulls a planet *in*, to a circular or elliptical orbit instead of a continuing straight line.

Some members of the Royal Society of London knew that an inverse-square law of gravitation would account for Kepler's Third Law, relating planetary years and circular orbit sizes. However, Kepler's elliptical orbits were too difficult for them; no one could show that an inverse-square law of gravitation would require such an orbit, or why Kepler's other law, the Law of Equal Areas, should hold. An appeal to Newton produced the astonishing answer that he had already solved the problem of all three laws and knew that they are necessary consequences of universal inverse-square-law gravitation.

Newton was finally persuaded to publish his work in greatly expanded form, in which he set forth not only his proofs of Kepler's Laws but a whole study of force and motion and universal gravitation in which he linked together: the gravity of falling bodies, the Moon's circular motion, planetary motions (Kepler's Laws), motion of comets, the tides, the shape of the Earth and ensuing differences of gravity, precession of the equinoxes, disturbances of the Moon's simple motion and planetary perturbations—all as parts of one tremendous structure of theory. As he himself wrote of his intentions:

> '... from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena; ... the motions of the planets, the comets, the Moon and the sea.'

This was success beyond all expectations. No wonder Newton's work was written about and expounded in every civilised country; and no wonder it came to be taught in school, generation after generation. Yet, somehow, the astronomical problems that called for his work and received his magnificent solution have been crowded out of present-day teaching for the majority of school pupils. We teach the Laws of Motion and make some use of them, in engineering and in atomic physics, but we miss the great drive felt by Newton's contemporaries and successors. How then are pupils to develop appreciation?

In planning the Nuffield Physics Programme, we wished to restore the balance to some extent, *not as a move towards historical teaching*, but to give our pupils a chance to appreciate Newton's Laws. And, far beyond that, we should let them see for themselves the part that good theory plays in science. We do not feel that we should interrupt the programme in Year 4 with astronomy when we are about to study Newton's Laws. This would be a most fitting place for historical study leading to Newton's work, but we are not sure that it would appeal to all pupils and we are anxious not to delay progress into kinetic theory and work with electrons. So we suggest that teachers should give at that point only a brief statement, that Newton, in stating his Laws, was stating his ideas about motion so that he could clear up and extend our whole knowledge and understanding of the solar system. And then we should promise to return to that in Year 5.

In Year 5's *Pupils' Text* we provide a historical study of knowledge and theories of the planetary system, from early information and empirical rules to Greek theories, on to Copernicus and Kepler and Galileo, so that pupils then feel the force of a great body of knowledge waiting for a concerted explanation and can thus see the full glory of Newton's work. We offer that as an example of the building of physical theory which is sufficiently simple for pupils to follow in their own reading and understand as part of their own knowledge. Pupils in school should see some example of good theory being built up, in a way that they can understand. Then, if it involves thinking that they have seen and worked with themselves, it will be something to be remembered, and theory will not be said to be 'mysterious, difficult thinking'.

Atomic theory is often suggested as an example of theory for pupils. However, we should have to provide, at this stage, so many ready-made results, that we would hand out the story without sufficient justification. It would form a poor prototype for this particular use. Instead, we suggest that Newtonian gravitation theory should be taught first, after building up a clear history of need—and then atomic theory can be described, almost ready-made, without harming the understanding of theory that we wish to give to all educated people.

If we now take a realistic look at the needs for Newtonian mechanics in Years 4 and 5 we see that pupils will need to:

(*i*) understand and measure momentum-changes, for kinetic theory and later for atomic collisions

(*ii*) know conservation of momentum as a general law; and use it in atomic collisions

(*iii*) use $F=ma$ with $s=\frac{1}{2}at^2$ to calculate deflection of electron streams, etc.

(*iv*) obtain the expression $\frac{1}{2}mv^2$ for kinetic energy.

(This is perhaps the most important single use that we shall make, in view of our discussion of Conservation of Energy.)

(*v*) use $F = ma$ with $a = v^2/R$ for motion in circular orbit, for planets and for electrons, etc., in Year 5

(*vi*) understand the meaning of a *newton* as a unit of force for use in pressure measurement in kinetic theory and for use in atomic physics; and understand *joule*, *watt*, and *volt*

(*vii*) and we hope they will profit from seeing a great theory being needed, then built up and then bearing fruit.

APPARATUS FOR DYNAMICS

We have a healthy tradition of illustrating Newton's Laws of Motion by experiments with trolleys. An earlier generation of pupils often saw these as demonstrations. Yet the arrangements for precise timing and uniform behaviour made the experiments seem complicated, or even confusing, to all but the ablest pupils. Sometimes that is a question of interest: it is not very exciting to watch a complex experiment and its analysis, when one does not feel personally involved. The laws being 'proved' did not strike the beginner as vital, essential, knowledge that he has been waiting for; so he was not likely to be intensely interested. Perhaps we could build interest more easily if the experiments were clear and pupils did them themselves.

Trolleys That is why we introduced 'roller-skate' trolleys and tickertape timers—all now in common use in teaching—for class experiments. These designs allow pupils to carry out their experiments and even make some ingenious modifications of their own. And we suggested 'standard' pulls of elastic threads as a measure of forces. Thus we hoped to lessen worries over *mass* and *weight* by avoiding gravity pulls for the accelerating forces.*

We let pupils take it for granted that two identical stretched threads in parallel provide twice the pulling force. Later we can proceed to use newtons as units for force, since pupils are already familiar with them as the empirical units on spring balances.

The trolleys must run on a *smooth, plane*, board. Although making and storing long runways with metal edges is troublesome, schools regard them as necessary parts of the trolley equipment. Most school labs only have room for 8 runways at work; then pupils must work in groups of four. Working in pairs would be far better—then pupils have a stronger sense of doing their own experiment—and it would be safer for the trolleys—whose wheel-alignment is easily ruined by a traffic accident. Our aim is not so much to provide a convincing demonstration of Newton's Second Law as to give pupils a personal feeling for forces and masses and their connection with motion—through pupils' own experimenting. Four pupils sharing equipment may feel they are really exploring motion; but with half a dozen pupils crowded round the experiments lose that flavour.

Timer The timer marks the paper tape drawn by the trolley every fiftieth of a second. Not only is the scheme of timing obvious, but pupils can *see* speeds by cutting the tape into sections, say, 10 vibrations long. By pasting those speed-strips side by side they can form a chart which makes acceleration obvious.

Dry ice pucks Trolleys and tickertape provide well for pupils' own experiments on force, mass and acceleration, on momentum changes, on conservation of momentum in one dimension, and on kinetic energy.

However, when we treat conservation of momentum we also want to show and analyse collisions in *two* dimensions. Trolleys will not provide for that. Furthermore we would like to reduce friction to insignificance in this very important test. So we suggest a demonstration with 'pucks' moving with practically no friction on a level lake of glass. Those 'hovercraft' pucks carry a store of solid carbon dioxide which produces a gas-bearing to support the puck almost without friction. The glass table must be very carefully levelled; then we can see collisions in a closed

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* If a trolley is pulled by a thread running over a pulley to a hanging load, we run into questions of gravity, weight and mass at too early a stage. The underlying story of that scheme is:

$$[\text{gravitational mass of pulling load}] \times [g, \text{ as a field-strength}] = [\text{inertial mass of trolley} + \text{inertial mass of load}] \times [a]$$

and however we simplify that—usually by concealing some of the distinctions—we give pupils difficulties.

system. Collisions are shown while pupils watch. Then a multiflash photo is taken and each pupil receives a print.

Other devices A *linear air track* gives a wonderful demonstration. It is such a delight to watch that each of us on first meeting it wants to adopt it. However, for the present programme, it is not recommended—even as an adjunct—for several reasons. The main reason: it is purely a demonstration device, and we feel that experimenting with motion, force and momentum should consist chiefly of *class* experiments for personal experience. Minor reasons: it is expensive; it needs careful storage and very careful adjusting before use; and even slight damage is apt to spoil its working. Some experimenters dislike the continual hissing of escaping air and the roaring of the air pump. And some have a feeling that this apparatus is too 'special', too remote from everyday machinery to give simple everyday teaching—yet in an age of hovercraft that feeling may disappear.

A two-dimensional *air table* (pierced with hundreds of tiny holes) is available. It is driven by the exhaust from a vacuum cleaner. It may supplant the glass table where dry ice is not easily available. (One has even appeared as a toy in an amusement park!).

Analysing the motion of pucks For timing 'frictionless' pucks a dragging tape is unsuitable. We need a timing device that does not interfere with the motion and yet is obvious to pupils and gives them records to analyse. 'Multiflash' pictures meet this need admirably, and have several other uses.

MULTIFLASH STROBOSCOPES, AND FROZEN MOTION

Multiflash pictures Illuminate the moving object by a regular series of flashes of light; or give the camera a regular series of glimpses of the object. Take a photo with several exposures on the same frame of film. Then speeds are shown by the distance between successive images.

The photo is taken in class, developed in class, and a magnified image of it is at once projected on a screen for public discussion and measurements.

Prints are made from that negative and each pupil receives a print to analyse. (Special printing paper enables the prints to be made in class with the room partially lit.)

The class thus has the thrill of seeing the whole process from start to finish in a normal class period. With practice, taking photographs, developing, and projecting can be done in 20 minutes.

Once pupils have seen a picture made and analysed their own copies, we may give them printed copies of photos of other events taken by a similar process. It would, however, be very poor teaching to use such printed copies if pupils had not first seen a real experiment done.

We urge teachers to experiment in expanding the uses of stroboscopic devices and multiflash photographs. This is a region of physics teaching where one's natural reaction is to avoid a technique that seems to all of us unfamiliar and likely to be uncomfortable for discipline. Those of us who have disregarded that plea of unfamiliarity find that the technique is so rich in its possibilities, and the results so quick and satisfying that we feel sorry not to have used it before; and pupils appreciate it so fully that it does not raise the discipline problems that we anticipate.

Multiflash illumination *Flashes of light* Light from a small bright source shines through slits in a spinning disc in front of the lamp. The camera lens is kept open and need not be limited by a slit. (There are dangers of spoiling the picture by stray light or by over-exposure of white backgrounds).

Camera glimpses. This is the easier method. A light disc with 5 or 6 radial slits cut in it is placed in front of the open lens of the camera. The disc is spun by a small electric motor. Small motors that are used for clocks do well.

An ordinary camera using 35 mm film is quite suitable—provided that it focuses down to 1 or 2 metres, has a lens with an aperture of f4 or better and has a shutter with a 'B' setting. The detailed techniques of exposure and development are explained in Appendix 2. A Polaroid camera is equally suitable, but is expensive and uses expensive materials.

The 'object' should be a small electric lamp (such as a toy lamp attached to a falling stone) or a small polished steel ball attached to the moving object and illuminated by a floodlight far away behind the camera. The latter arrangement gives an excellent record, because the ball forms a small virtual image of the lamp which makes a tiny spot on the photograph. If the spinning shutter has a narrow slit, the spot is small even if the object is moving fast—provided the lens aperture is also made narrow. If the shutter has a wide slit, each spot is drawn out into a streak which indicates speed by its length.

Xenon flasher A gas discharge tube regularly pulsed makes intense flashes of very short duration—hence sharp images on film. This is a luxury item, outside our normal suggested equipment; but it is a delight to use, particularly for 'frozen' motion.

'Frozen motion': stroboscopic illumination Any motion that repeats regularly can be made to appear stopped by regularly flashing light of the right frequency. A motor-driven disc in front of the lamp with compact filament does well*; or the luxury pulsed gas discharge tube. Suggestions for uses: a stream of pulsed water drops*; water ripples; standing waves on a string; the blade of a vibrating timer.

The Nuffield equipment Once a teacher has multiflash equipment and has gained some practice in using it, he will be tempted to try it for many other demonstrations. He certainly should put it to several uses in Year 3 as well as Year 4; yet such demonstrations should not be allowed to crowd out the trolley experiments in which pupils gain strong personal experience.

Equipment for both trolley experiments and multiflash pictures with frictionless pucks is expensive. But, in considering the cost, schools should remember that these are not still more complicated experiments for proving Newton's Laws: they are ways of simplifying the story to give understanding.

The conservation of momentum, for example, is one of the most important fundamental principles of physics. In the past, few pupils have ever been able to see a convincing demonstration of it, or even a reliable test; but multiflash pictures and 'frictionless pucks' of one form or another afford an easy, convincing test of momentum-conservation *in two dimensions*. We suggest that as an essential experiment in Year 4.

* In the picture of the pulsed water drops there is a lens, placed to form an image of the filament on the slit of the spinning disc. That lens is *not* needed with our suggested compact light source, which has such a small filament. It is a refinement which might be helpful with a lamp that has a long filament.

SCIENTIFIC EXPLANATIONS

Year 4 is a time for growth in the meaning of 'explanation'. In earlier Years we 'explained' things in science by giving extra information. Secretly, without even saying so—and certainly without being comprehended if we tried to say so—we were explaining in the proper scientific way: attaching unfamiliar or difficult things to things already known. That is, after all, what 'explanation' means in science.

Children hope to find us explaining by giving the 'really true cause of things'; but in fact we only link one thing with another. For example, we 'explain' a lightning flash by saying 'it is a big electric spark'. That tells us nothing about a spark but it reduces the number of unknowns. It offers to decrease the hold of superstition. In that, as Lucretius said, 'Science [in his Latin, *ratio*, for reasonable knowledge] frees man from the terror of the gods'.

We can, later on, 'explain' an electric spark by saying that is an event in air in which there are many ions, driven so hard by an electric field that they make more ions by collision, and so on. All that, if we examine it carefully, does little more than link a spark to things which we have seen in a lot of other experiments on gases being bombarded, flames conducting currents, etc.

If we refuse to be disappointed and claim that our explanation goes deeper than that, we find that we are linking the spark to some models of gases and things in them: a picture of molecules, a picture of an electron and a model of an electron being ripped out of the molecule; and that leads us back to explanation as a linking—this time, linking through our models to our knowledge of collisions of billiard balls and things like that.

One of the best examples is the explanation of the Moon's motion around the Earth. We say the Moon is just falling under the action of (diluted) gravity, like a cricket ball, and we feel satisfied. Yet we have there no ultimate explanation of gravity.

Though many of us enjoy scientific explanations like that and wish to endow them with special virtues beyond mere linkage with the more familiar, we should be wise in our teaching to think of explanation as a linking—connecting 'new', unfamiliar, knowledge to 'old', accepted, knowledge.

PROPORTIONALITY

Much of our knowledge of physics is expressed in the form of proportionalities. Most of us in teaching physics give pupils no preparation for dealing with proportionality but wait until an important case arises. Then we expect pupils to understand the relationship which has appeared: and, when we find that some of them have considerable difficulty in understanding proportionality or making use of it, we are surprised and disappointed and blame our colleagues who teach mathematics. We then resort to earnest measures of exhortation and explanation, but with only moderate success—the stumbling-blocks often remain.

It is suggested by some critics that we have the good examples in physics with which to make a fresh start and teach proportionality successfully and that we should therefore not assume previous knowledge or skill. Instead we should start by explaining very carefully what proportionality is and how to use it, before we use it to codify our knowledge of physics. For teachers who wish to experiment with such a preparation before using it for *force*, *mass* and *acceleration*, we offer suggestions in the *General Introduction* issued at the same time as *Teachers' Guide* Year 3. See also the Note on 'The Remarkable Role of the Word "Constant" in Science' in the General Introduction.

LASTING OUTCOMES: WONDER AND DELIGHT .... KNOWLEDGE ....

PAST: Nuffield Years 1 & 2 or Combined Science

GENERAL ACTIVITIES & OUTCOMES

Acquaintance

Experimenting: enjoyment of doing one's own experiment

ACQUAINTANCE
materials (informal survey)
instruments: balance, microbalance; magnifying glass, microscope; thermometer, Bourdon gauge; barometer; Bunsen burner (stopwatch)

GUESSING ESTIMATES

BEHAVIOUR of lever, springs; (laws?)

FORCES
examples; measurement by springs;
1 newton as arbitrary unit

ATOMS & MOLECULES
informal naming: simple teaching-models,
Brownian motion; oil film estimate

ENERGY from fuel, forms, interchanges, (work)
cloud chamber, spark counter; heat,
measurements and transfer

ELECTRIC CIRCUITS acquaintance and play
with lamps and batteries; simple ammeter, fuses

Nuffield Year 3

GENERAL ACTIVITIES & OUTCOMES

Doing one's own experimenting with water ripples, lenses & images, forces & motion; electromagnetism

Thinking about models: idea of laws

(1) WAVES
knowledge of behaviour gained by own experimenting
(acquaintance with interference)

(2) OPTICS I
rays & images; eyes, instruments

(3) OPTICS II
spectrum & colour
(interference, theories)

(4) FORCE & MOTION
experiments on acceleration,
projectiles,
inertia

(5) GASES
molecular model; expansion etc.
Boyle's Law

(E) ENERGY (special chapter for catching up):
forms, interchanges,
(work), (power)

(6) ELECTROMAGNETISM
fields, meters, motors, dynamo,
oscilloscope

(7) VOLTAGE AND POWER
use of voltmeter (power), house wiring

(8) ELECTROSTATICS
charges
(fields)

(9) THEORY OF MAGNETISM
as an example

FLOW CHART FOR YEAR 4

.... KNOWLEDGE .... INTELLECTUAL SATISFACTION

PRESENT: Nuffield Year 4

GENERAL OUTCOMES

Connected knowledge

Ideas of use of theories and models

Intellectual satisfaction

UNIFORM ACCELERATION
$s = ut + \frac{1}{2}at^2$, etc.

NEWTONIAN DYNAMICS
$F = ma$
conservation of momentum
kinetic energy

KINETIC THEORY yielding speed, spacing, size of molecules

ENERGY CONSERVATION

ELECTROMAGNETISM
a.c.; voltage, power; power transmission, oscilloscopes

ELECTROSTATICS
electroscope
charges and forces, fields;
Millikan experiment

FUTURE: Nuffield Year 5

GENERAL OUTCOMES

Connected knowledge

Ideas of use of theories and models

Pictures of atom models

OPTICS
interference & diffraction
comparison of theories
electromagnetic spectrum

ORBITAL MOTION $a = v^2/R$
applications to:
Earth satellite, planets
e/m for electrons
mass spectrometer

PLANETARY ASTRONOMY
as an example of theory:
history of models
Kepler's Laws
Newtonian theory

RADIOACTIVITY
atomic and nuclear information

ATOMIC MODELS
simple model
Rutherford atom
wave model

PUPILS' DEMONSTRATIONS FOR REVISION

USES OF THEORY

CHANGES OF EXPERIMENT NUMBERS

Experiments in original *Guide to Experiments IV* omitted in revised programme:

Old numbers: 8, 10, 12, 13, 21a, 21b, 26, 29, 30, 31, 33a, 33b, 42, 50, 53, 66, 75b, 82b, 87a, 87b, 88, 91b, 93a, 96, 102b, 103, 114, 156, 157, 160, 161, 164, 165, 166.

Experiments in original *Guide to Experiments IV* converted to picture or chart in *Pupils' Text 4* of the revised programme:

Old numbers: 109, 112c.

Experiments in original *Guide to Experiments IV* postponed to Year 5 in revised programme:

Old numbers: 130, 131a, 131b, 132, 133, 163.

Experiments in original *Guide to Experiments III* postponed to Year 5 in revised programme:

Old numbers: 37, 54d, 59, 61, 63, 66b, 73, 88c, 90a, 90b, 96, 97, 99b and c.

New	*Old*	*New*	*Old*	*New*	*Old*	*New*	*Old*	*New*	*Old*
1	1	31	16	65	68	89c	106c	119	145
2	2	32a	17a	65X	69	89d	106d	120	146
3	‡67	32b	17b	66	70	90a	105b	121	144
4	‡47	33	18	67	82a	90b	105a, c	122	147
5	3	34	64	68a	71, 73b	91	107	123	(148)
6	4	35	24	68b	72	92	111	124	151a, b, d
7	9	36	27	68c	73a	93	121	125	151c, d
8	5	37	28	68X	101	94	112a	126	151e
9a	‡64	38	40, 53	69	74	95	112b	127	151f
9b	56	39	41a	70	76	96	113	128	151f
9c	‡50	40	41b	71a	75a	96X	—	129	153
10	‡51	41	43	71b	77	97	112d	130	152
11	19	42	44	72	78	98	112e	131	149a
12	20	43	45	73a	79a	99	115	132	149b
13	22	44	46	73b	79b	100a, b	116	133	149c
14	57	45	47	74X	86	101	117	134	150
15	6	45X	48	74	80	102	118	135a	154a
16	23	46	51	75	81	103	119	135b	154b
17a	7	47	49a	76	89	104	(169)	136	154c
17b	7	48	49b	77	90	105	120	135X	154d
17c	11	49	52	78a	—	106	122	137	155
18	32a	50	54	78b	91a	107	(123)	138a	158
19	32b	51	55	78c	91c	108	125a	138b	159
20	25	52	58	79	92a	109	125b	138c	—
21	36	53	58	80	92b	109X	125b	138d	—
22	34	54	59	81	‡‡93e	110	126	138e	—
23	35	55	60	82	93b	110X	127	139a, b, c	‡95a ‡99a
24	38a	56	60b	83	94	111	128	140a	162a
25	37	57	61a	84	95	111X	129	140b	162b
26	38b	58	61b	85a	97a	112	(138)	141	170
27	39	59	61c	85b	97b	113	139	142	167
28a	15(1)	60	62	86	99	114	140	143	168
28b	15(2)	61	63	87	100	115	141a		
28c	15(3)	62	65	88	98	116	141b		
29	—	63	64	89a	106a	117	142		
30	14	64	67	89b	106b	118	143		

‡ Number in original *Guide to Experiments* Year III. ‡‡ Number in original *Guide to Experiments* Year V.

List of Experiments

†Experiment suggested in Year 3.

†Experiment suggested in Year 3.

Class Experiment 57
Energy measurements with a catapult and a trolley: strain energy to K.E.

Demonstration 58
Table tennis with a trolley started and stopped by catapults: energy changes

Class Experiment 59
Table tennis with a trolley and catapults (*optional*)

Demonstration 60
Free transport from here to there along the table by borrowing some K.E.

Demonstration 61
Massive pendulum to show energy changes

Demonstration 62
†Downhill-and-uphill motion: Galileo's guess

Demonstration 63
†Galileo's pin and pendulum experiment

Demonstration 64
Kinetic energy disappears: inelastic collisions

CHAPTER 6 GASES I

Demonstration 65
Model of atoms in a solid

Experiment 65X
Model of a solid using pupils

Class Experiment 66
†'Teaching model' to represent a liquid

Demonstration 67
Model to show bombardment making pressure

Demonstration 68a
†Model of air molecules: three-dimensional model for kinetic theory

Class Experiment 68b
†'Teaching model' to represent a gas: marbles in a tray

Class Experiment 68c
†'Teaching model' of Brownian Motion: with marbles in a tray

Experiment 68X
Photograph of marbles in motion (optional)

Class Experiment 69
†Brownian motion of smoke in air

†Experiment suggested in Year 3.

Demonstration 70
†Boyle's Law

Qualitative Demonstration 71a
Gas model used to illustrate Boyle's Law

Class Experiment 71b
Crowding marbles in a tray: another illustration of Boyle's Law

Demonstration 72
Barometer

Demonstration 73 (Method A)
Measurement of the density of air

Demonstration 73 (Method B)
†*Alternative method for rough measurement of the density of air*

Demonstration 74
Quick comparison of the densities of water and mercury

Demonstration 74X
Density of water

Demonstration 75
†Model showing thinner atmosphere higher up

CHAPTER 7 GASES II RICHER PREDICTIONS

Demonstration 76
†High speed molecules? Bromine 'gas' diffusing in air

Demonstration 77
High speed molecules. Bromine diffusing in vacuum

Demonstration 78a
†Change of volume, liquid to gas, using petrol

Demonstration 78b
Change of volume: liquid nitrogen to gas (*optional alternative to 78a*)

Demonstration 78c
Change of volume: solid CO_2 to gas (*optional alternative*)

Demonstration 79
†Longitudinal wave along a slinky

Demonstration 80
Longitudinal wave along a line of pucks

Demonstration 81
Waves along a line of trolleys (*optional*)

Demonstration 82
Speed of sound

Demonstration 83
Critical test: Speed of sound in air at different pressures (*optional*)

Demonstration 84
Floating and sinking gases H_2 and CO_2 in air

Demonstration 85a
Diffusion of gases

Demonstration 85b
Diffusion of gases (*optional alternative*)

CHAPTER 8 GASES III A GREATER PREDICTION AFTER A HARD CLIMB

Demonstration 86
Measuring the diffusion of bromine in air

Class Experiment 87
Watching a random walk: mean free path

Class Experiment 88
Test of a random walk

Calculation
The bromine estimate leads to mean free path

CHAPTER 9 ENERGY AND ITS GRAND TOTAL: CONSERVATION

Demonstration 89a
Exchanging heat between hot and cold water

Class Experiment 89b
Measuring heat

Class Experiment 89c
Measuring heat by burning alcohol

Class Experiment 89d
Estimate the heat given to aluminium

Class Experiment 90a
Converting mechanical energy to heat

Experiments 90b
Converting mechanical energy to heat (*optional*)

Class Experiment 91
The 'waterfall' of lead: measurement of 'J'

CHAPTER 10 POWER AND HUMAN ENERGY

Demonstration 92
Comparison of powers of electric lamps

Demonstration 93
Comparison of electric motors

Class Experiment 94
Pupils measure their own useful power

Class Experiment 95
Pupils measure useful power for an all-day job

Class Experiment 96
Energy-transfer box for power-transfer

Experiment 97
Working against a band brake (*optional*)

Home Experiment 98
Output of power, cycling up a hill (*optional*)

CHAPTER 11 ELECTRIC CIRCUITS WITH VOLTMETERS

Demonstration 99
Series circuits and branching circuits

Demonstration 100 a and b
†Water circuit

Demonstration 101
Electrolysis of copper sulphate solution

Demonstration 102
Electrolysis of water (*optional now*)

Demonstration 103
Experiments with capacitors

Demonstration 104
Dancing men: preparation for Millikan

Demonstration 105
Comparing lamps

Demonstration 106
Lamps in parallel

Class Experiment 107
The voltmeter as a cell counter

Class Experiment 108
Using a voltmeter

Demonstration 109
Connecting a voltmeter

Demonstration 109X
Connecting a voltmeter (*optional extra, to help a slow group*)

Class Experiment 110
Does your voltmeter measure what it is supposed to?

†Experiment suggested in Year 3.

Class Experiment 110X
Calibrating a voltmeter (*optional*)

Demonstration 111
p.d. and e.m.f.

CHAPTER 12 OHM'S LAW AND OTHERS

Demonstration 112
Ohm's Law: a simple direct approach—without a voltmeter

Class Experiment 113
Ohm's Law

Class Experiment 114
Temperature-change and resistance

Demonstration 115
Volts and amps for copper sulphate

Demonstration 116
Volts and amps for water (*optional now*)

Demonstration 117
Volts and amps in neon gas

Class Experiment 118
Effect of temperature changes on conductivity

Demonstration 119
Effect of strong heating on common salt and paraffin

Demonstration 120
Current in a heated glass rod

Demonstration 121
Effect of strong heating on a thermistor (*optional*)

Demonstration 122
Conductivity of germanium (*optional*)

Class Experiment 123
Transistor

Class Experiment 124
Measuring resistance with voltmeter and ammeter

Demonstration 125
Measuring resistance with voltmeter and ammeter

Experiment 126
Measure the resistance of a voltmeter itself (*optional advanced puzzle*)

†Experiment suggested in Year 3.

Class Experiment 127
Making an ammeter (*optional*)

Class Experiment 128
Making a voltmeter (*optional*)

Class Experiment and Demonstration 129
Making an electric arc work from the mains

Class Experiment 130
Fault finding (*optional*)

CHAPTER 13 POWER IN ELECTRIC CIRCUITS

Class Experiment 131
Power transferred in a lamp

Class Experiment 132
Power transferred in a motor

Class Experiment 133
Further experiments with a motor (*optional*)

Demonstration 134
Power of a fractional horse-power motor

Class Experiment 135a
d.c. model power line

Demonstration 135b
d.c. model power line at high voltage

Class Experiment and Demonstration 136
Measurement of power in model power line (*optional*)

Class Experiment and Demonstration 135X
a.c. power line (*optional now*)

Class Experiment 137
Electrical measurements of the specific heat capacity of aluminium (*optional*)

CHAPTER 14 ELECTRONS

Demonstration 138a
The diode as an electron gun

Demonstration 138b
The diode as a rectifier, shown on oscilloscope

Demonstration 138c
Solid-state diode as a rectifier

Class Experiment 138d
Solid-state diode as a rectifier

Class Experiment 138e
Full wave rectifier with solid-state diodes (*optional*)

Demonstration 139
†Electrostatics for catching up

Demonstration 140a
†Fine-beam tube

Demonstration 140b
Fine-beam tube: deflection of beam using alternating voltages

Film 141
Millikan: 'Are there electrons?'

Demonstration 142
Ions in a candle flame

Demonstration 143
Radium makes ions in air

†Experiment suggested in Year 3.

SECTION I

MECHANICS

In our Nuffield programme we have tried to increase the emphasis on electromagnetism and to add more 'atomic physics', and at the same time we encourage pupils to think about the ways in which theory and experiment combine to build a well-understood coordinated body of knowledge that they can enjoy possessing.

In the past, Newtonian Mechanics formed the traditional backbone of such a body of knowledge. Now we do not want pupils to find that backbone too massive and rigid. So we urge teachers to treat this section lightly, skipping so that pupils maintain interest and enjoyment.

Chapter 1 deals with motion, acceleration and force—for 'catching-up' if pupils missed some of this introduction in Year 3.

Chapter 2 makes a serious study, with experimental illustrations, of Newton's Second Law of Motion.

Chapter 3 deals with Newton's First Law and Inertia.

Chapter 4 changes to a treatment of Newton's Second Law with momentum and proceeds to Conservation of Momentum.

Chapter 5 deals with kinetic energy—leaving general Conservation of Energy to Chapter 9.

CHAPTER 1

MOTION

Experiments for catching up; acceleration; free fall; weightlessness

ACCELERATION IN FREE FALL

Re-open the problems of force and motion—introduced in Year 3 but left after a brief look.

MULTIFLASH PICTURES

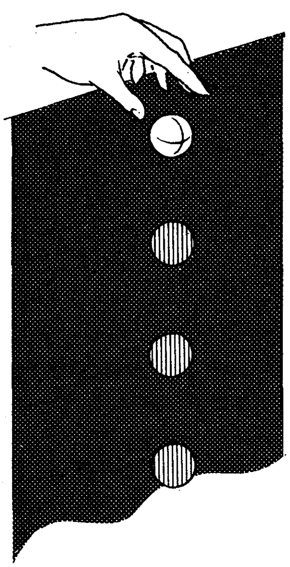
A different method Start the investigation of motion with a multiflash experiment—a series of stages all photographed on one picture. This modern method will give an intriguing introduction before we return to trolleys.

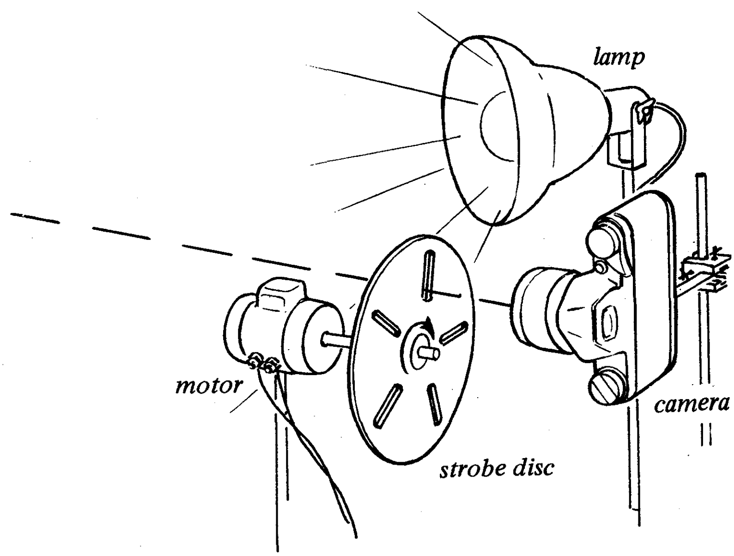
Demonstration 1 Free fall in multiflash photographs

Apparatus

1 steel ball (2–3 cm diam.)	item 131A
1 camera	133
1 motor-driven stroboscope	134/1
2 retort stands and bosses	503, 505
rods for camera and stroboscope	504
1 metre rule	501
1 slotted base for metre rule (or stand and clamp)	30
black cloth or paper for background	
1 lamp‡	218 or 557

‡ The lamp should be a floodlamp or photoflood or, best of all, a small slide projector, pointed horizontally with its beam reflected down by a mirror at 45°.





Procedure

Set up the motor-driven stroboscope in front of the camera. Illuminate the ball strongly *from vertically above*. Place a black background behind the path of the ball. The essence of success here is strong contrast between the bright ball and its surroundings; so the rest of the room should be three-quarters blacked out.

Set the camera to 'B'; and start the motor-driven stroboscope rotating.

Give a countdown. One pupil releases the ball. Another operates the camera and opens the shutter just before the ball is dropped, and holds it open.

Give each pupil a print. Include a vertical measuring stick in the picture, so that the photo may be used later for an estimate of g. The strip should have alternate centimetres, marked black and white—a plain metre rule is not so good. Also record the strobe frequency.

Note: See Appendix I for details of multiflash photography.

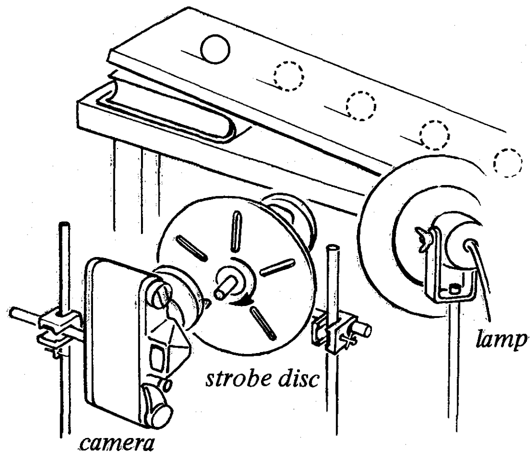
Diluted gravity With the multiflash equipment already set up it is easy to record another motion, a ball rolling down a hill.* This too is for a quick look.

Demonstration 2 Motion down a hill in multiflash photographs *(OPTIONAL EXTRA)*

Apparatus

1 motor-driven stroboscope	item 134/1
1 steel ball (2–3 cm diam.) (or a trolley carrying a bright spike)	131A
1 camera	133
3 retort stands and bosses	503, 505
rods or clamps for camera, strobe, and lamp	504
1 sloping plank	(or a runway 107)

The steel ball must be well polished. If a spike is used, cover it with chrome Sellotape (or aluminium foil).



Procedure

Set up an inclined plank or runway with slope about 1 in 10. Let the steel ball roll down this incline, starting from rest.

Place the camera at one side of the track, with its axis perpendicular to the ball's path. Place the lamp beside the camera, so that it illuminates the ball all along its path.

Start the stroboscope and open the shutter just before the ball is released. Close the shutter when the ball passes out of the field of view.

Give each pupil a print (See Appendix).

The frozen pearls With multiflash now in use this is a good time to show the 'frozen' water drops—just for delight. No measurements are needed, but there is one important observation: the evidence of constant horizontal velocity.

* Some pupils might be challenged to take some multiflash pictures of still other motions: a table tennis ball thrown in a parabola; a football given a kick; or the bob of a pendulum swinging to and fro. Some might return to this in Year 5 and photograph an elliptical orbit.

Demonstration 3 'The frozen pearls': pulsed water jet parabola

Apparatus

1 compact light source	item 21
1 motor-driven stroboscope with disc with 5 slits	134/1
1 timer	108/1
tank for constant pressure head, with rubber tubes for supply and overflow	166
rubber tube, 1 metre, thin walled, external diam. about 8 mm	562
1 L.T. variable voltage supply, a.c. (or variac (78), or transformer and rheostat)	59
4 retort stands, bosses and clamps	503–506
1 Hoffman clip	522
1 bucket	533
white screen or wall	
short glass tube for jet (e.g. eye dropper)	102
[grid to make vertical lines‡]	

‡If the experiment is shown only for pleasure, the grid is not needed. If it is shown for information as well, the grid is essential. The grid held beside the stream of drops casts shadows of evenly spaced vertical lines, for visual analysis of the pattern.

The grid may be a set of vertical wires, spaced 2 or 3 cm apart on a frame, or a sheet of perspex with lines which will cast shadows. Or the shadow of the 'pearls' on a plain paper screen can be marked with a pencil and measured.

Arrangement

The timer makes a stream of water break up into a regular series of drops which can be 'frozen' by stroboscopic illumination.

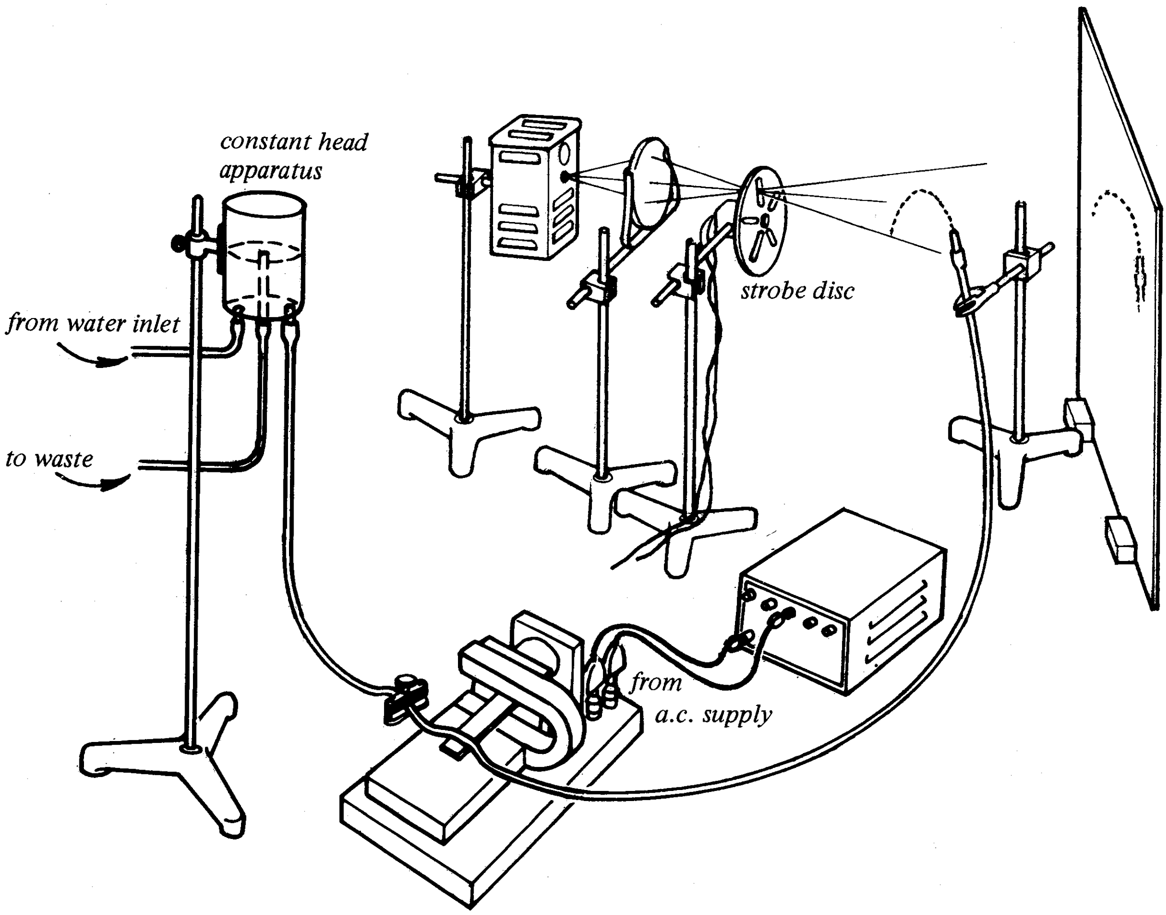
Water from a constant pressure supply (or a syphon supply from a bucket) held high above the bench, flows out through a rubber tube pinched by a Hoffman clip to reduce the flow to a small stream.

The stream emerges from a short glass tube drawn out to make a jet.

The height of the constant-pressure tank should be such that if the stream is directed vertically it rises 15 to 30 cm above the jet.

To make the stream break up regularly the rubber tube that runs from the tank to the glass jet is draped over the blade of the vibrator.

The Hoffman clip must be close to the vibrator and it *must be upstream* from it.



Then the vibrating blade jolts the rubber tube with a gentle pumping action so that drops are formed steadily, 50 a second.

Tilt the jet to make a parabola. Arrange the lamp to throw a shadow of the stream on a screen. Place the strobe disc in front of the lamp. Use a disc with 5 slits, not 6. With the synchronous motor running at 300 rpm there will be 25 flashes a second, which will 'freeze' the motion of the drops.

Procedure

Vary the flow rate and the timer voltage until a clear stream of drops emerges from the jet.

Cast a shadow of the stream *without* the strobe disc. The stream will look continuous.

Then interpose the strobe disc close to the lamp.

To show that the horizontal motion of each drop is constant, place the grid of vertical wires (or lines on perspex) beside the stream. Adjust the angle of the jet or the speed of the water so that each shadow of a drop (or every second or third shadow) falls on a line.

Notes

1. For easier control, pass the rubber tube *under* the blade so that it is actually squeezed 50 times a second, but this is not necessary.
2. For sharper shadows, arrange a lens to form a real image of the lamp filament on the strobe disc's slit, as in the diagram; but this is not necessary if the compact light source is used.

TAPE EXPERIMENTS FOR CATCHING UP (denoted by †)

Pupils who enter the programme now need a gentle introduction to timers and tape. Although some other pupils may seem to need revision, it will be better to wait and let them remember the earlier work as they press on with the more advanced experiments ahead. Revision now might be comforting, but will later lead to the complaint 'too much work with trolleys'.

For newcomers we suggest two experiments to try for themselves. But first they should be shown the working of a ticker-tape timer. Explain that it marks the tape at equal intervals of *time*, not at equal distances.

(If they have used hand stroboscopes before let each pupil use one to look at a timer—but otherwise avoid what would be a long diversion.)

Offer an experiment with uneven motion just to use the timer and learn the meaning of a tape-chart. Then offer an experiment to see motion with unchanging acceleration being shown by tape-charts.

Give a warning about marking tapes: *'Mark your first dot 0 not 1'*. (Beginners marking off a 'tentick' are apt to label the dots 1, 2, 3 . . . 10 and have only 9 ticks.)

† Class Expt 4 Timing your own walk: a first experience with timer and tape

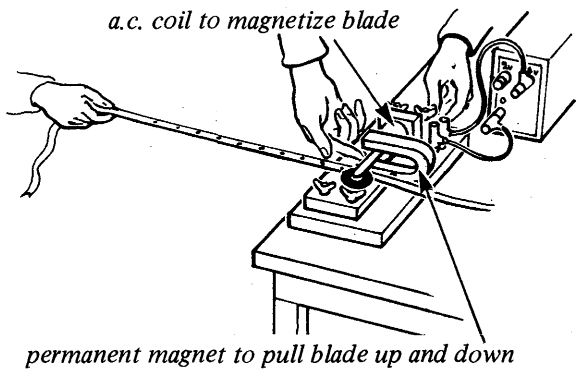
(OPTIONAL intended for pupils who missed the work with trolleys and tapes in Year 3)

Pupils work in pairs.

Apparatus

Each *pair* will need:

1 timer	item 108/1
1 roll of ticker-tape (preferably gummed)	108/4
1 transformer	27



Procedure

Pupils follow these instructions:

* * * * *

Timing your own walk Use the vibrating timer to record your walking trip on tape. The timer hits the tape regularly and makes a mark 50 times a second. We call the time from one hit to the next one *tick*. So the dots on the tape are spaced *one tick of time* apart.

You will find ten ticks make a useful length of time, so we shall call that one '*tentick*'. That is the time from dot no. 0 to dot no. 10 on the tape. (Also from dot no. 10 to dot no. 20.)

Let your partner operate the timer while you walk away from it, pulling the tape. Walk fairly slowly. If you run the timer may mark the tape unevenly.

The dots are made by the vibrating blade at regularly spaced *times*. But they will not be equal *distances apart* along the tape, because you do not walk at absolutely constant speed.

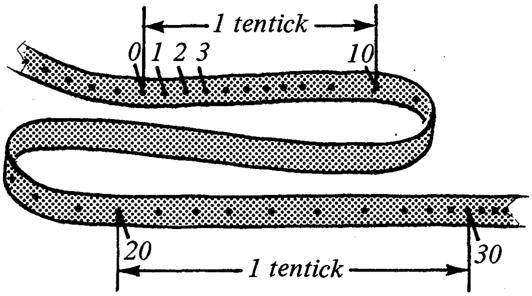
Find out how far you walked in the first 10 ticks. Measure from dot no. 0 to dot no. 10. That is how far you walked in one tentick.

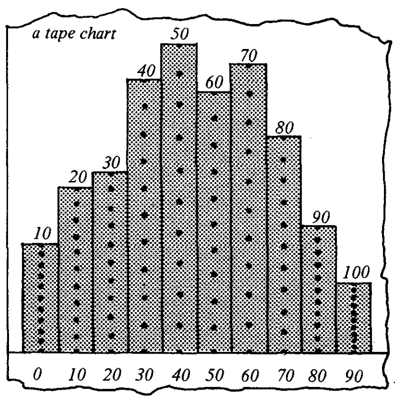
Make a tape-chart. Cut off the strip of tape for the first tentick period of your walk and paste that on a sheet of paper.

Cut off the next tentick strip and paste that strip beside the first one, and then the next, and so on, for all your tape. Each strip shows how far you walked in one tentick of time. Paste all the strips on your chart with their feet on the same line at the bottom; then their heads will show you how your speed changed as you walked.

* * * * *

Each pupil should make (and keep) his own tape chart.





Hold a 'picture gallery' of tape charts. Ask what they show.

Explain that this chart is only a preliminary example; and that we are going on to deal with different forces pulling a trolley along a level table, and different chunks of matter (several trolleys) being pulled along, so that we shall know more about rocket motion, satellite motion and the general problems of modern transport engineering and astronomy and 'atomic physics'.

† Class Expt 5 Car coasting down a hill: ticker-tape technique

(OPTIONAL EXPERIMENT FOR CATCHING UP) This is intended for pupils who missed Year 3. We do not recommend it as 'revision' for pupils who have used trolleys and tape before.

Pupils should work in pairs, or groups of four at most. Each pair or quartet will need:

Apparatus

1 dynamics trolley	item 106/1
1 ticker-tape timer	108/1
1 runway	107

Preparation

Make sure each sloping runway is straight. Place a support under the middle if there is any sign of sag.

Procedure

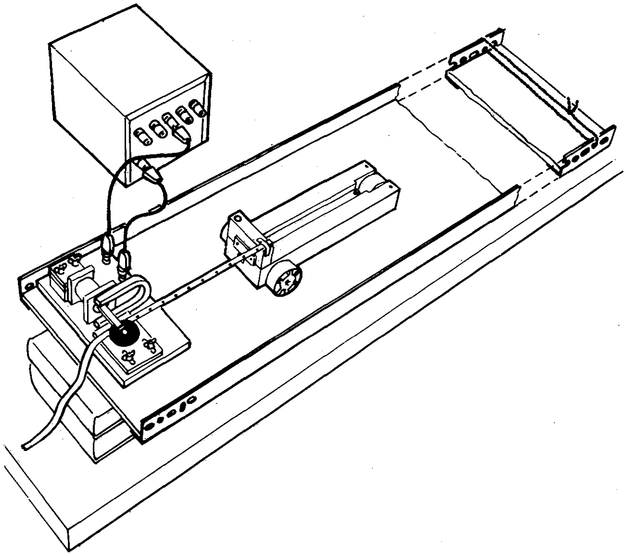
Pupils follow these instructions:

* * * * *

Tilt the runway to make a slope of about 1 in 10 by placing blocks of wood or books under one end.

Let the trolley run down the incline, starting from rest and dragging tape through the timer.

Repeat the run, so that each partner obtains his own tape.



Cut your own tape into tentick strips. Paste up a tape-chart. Put all the tentick strips side by side with their feet all on a horizontal line.

Look at your chart. *What does it tell you about the motion?*

* * * * *

When each pupil has his own tape-chart, hold a picture gallery of charts. Ask what the charts show about the motion.

DISCUSSION WITH TEACHERS: EARLY ATTITUDES

{Before pupils embark on careful measurements to illustrate Newton's Laws we should raise the questions that involve those Laws. Otherwise pupils will work blindly in an uninspired way that propels no scientist. Or else, if we have insisted on the outcome to be expected, they will just collect results for a foregone conclusion.}

{**Unfinished arguments and unanswered questions** These sometimes have a constructive action. They are of the essence in scientific research. Yet all of us who teach hesitate to start a problem in physics and leave it unfinished, or ask a question and leave it unanswered for a long time. Our hesitation is well founded because both we and our pupils expect the teaching to go straight through to a definite result. Leaving things unfinished is likely to make all of us feel confused and doubtful. So we should not often leave things unfinished *unless* we can do that with the light touch of the advertising man—present our questions as an interesting puzzle—or come to a dead stop in our argument, with pupils feeling that they are cooperating in the search and are glad to have gone so far, even though both they and we find a barrier.}

{Such use of unanswered questions or unfinished problems must depend strongly on the pupils' frame of mind which the teacher can encourage. Given the right repetition, they can be very powerful, the essence of helping pupils to learn for themselves.}

Applications We need questions which relate to real life or appeal to pupils' own interests, questions that bring in some *application* of the physics that is being studied. It is difficult to suggest examples of applications that will suit all classes. Such examples come best with the full force of the teacher's own interest; so we hope teachers will keep an eye open for interesting applications and make use of them.

{**Views of science** Most of our pupils have a clear, almost rigid, view of science as completely 'right'. They believe that science tells the true story of real nature (which has been 'waiting to be discovered'); that science can give the correct explanation of every phenomenon. Scientists, as pupils see them, find out and *know*, and they can *tell*: they set forth the facts and reveal the scientific explanation. There is considerable truth in that view; but it is too rigid: it is out of tune with modern scientists' views of their work.}

{Today, we are more humble about 'knowing all the facts'. In our experimenting we can only go by what our instruments tell us; and we now know that our experimental work is bound by severe limitations that are inherent in nature. When we interpret our experiments, even while we are conducting them, we make assumptions: we plan and infer in terms of a model, in the light of our picture-of-the-moment of nature.}

{Science today is not just a pile of measured results like a table of densities or some values of g; nor is it a set of formulae connecting measurements, like $s = \frac{1}{2}gt^2$. We try to build a connected frame of knowledge, in which models of nature—sketched by imaginative thinking based on experimental results—enable us to think and plan, to check the models themselves to some extent, to predict, to guide more investigations, and over all to discuss our own knowledge.}

{It is the growing edge that most scientists enjoy, the doing and thinking to extend the framework of knowledge, rather than the possession of facts and rules already accumulated. Unless young people understand something of that attitude they will miss the spirit of modern science.}

Theories already? {For that reason, we want pupils to have glimpses of theory—in the making and in use—now at this O-Level stage, and not wait for a sixth-form treatment of theory that they may never meet.}

{In Year 3 we offered a simple magnetic theory whose fruitfulness is obvious to beginners. That comes at the end of Year 3; and we trust teachers trying our programme will not omit it through lack of time or equipment or—as one might think—lack of pupils' interest. The interest will certainly be there, if we put the purpose clearly; and the time is well worth saving from an overdose of trolley practice or a study of gas expansion. An early understanding of theory will last longer and be of greater value. Nor should that be postponed. We rely on it to have sown seeds of interest some time before we now tackle kinetic theory in Year 4 and gravitational astronomy in Year 5.}

{In Year 4 we trust teachers will develop a theory of gases as fully as pupils' skills and interests permit. Here again, successful learning will bring rich rewards. The rewards increase exponentially with the depth of understanding and variety of uses that we can give for the theory.}

{Therefore we need to prepare the ground for *speculation*. That is why we hope teachers will offer problems that promote discussion. We need to soften our pupils' picture of the scientist as the man who knows, who has found out with complete precision by experiments. If pupils can think of the scientist as the man who has some knowledge but knows its limitations, as the man who is finding out, who enjoys discussing questions as much as solving formal problems, as the man who *thinks*, we shall have brought those young people much nearer to modern science.}

DISCUSSING PLANS WITH ALL PUPILS

This may be a good time to tell pupils about plans and offer them a look into the future of the programme.

This year pupils will go on from the first topic, force and motion to a theory of gases with molecules treated by Newton's Laws, to make remarkable predictions and increase our general understanding;
then to a new discussion of energy and conservation of energy, with heat fully in the energy family at last;
then more work with electric circuits and voltmeters and power transmission:
and finally experiments with an electron stream in a vacuum and a very important experiment to measure the electric charge of a single electron.

Each of those later developments requires a knowledge of force and motion and an understanding of kinetic energy which itself uses a knowledge of force and motion.

Next year (Year 5) pupils will read the development of good theories in astronomy, do experiments with alternating currents, make measurements on a stream of electrons, measure a radioactive half-life and see the building of increasingly successful models of atoms.

This year's first topic, the Laws of Motion, is an important part of our knowledge of science. It is useful in analysing the behaviour of atoms and parts of atoms (such as electrons) because we make those tiny things move and we change their motion when we are trying to find out about them. It is useful in solving some great problems in astronomy (for example: What keeps the Moon moving? Why does it move in a circle?). It is of great use in engineering in dealing with trains and cars and planes and in arranging to fire rockets and satellites successfully. In general the present work on force and motion is a preparation to enable pupils to know how we build our models for understanding nature.

(To a very fast group we might even add: 'You have probably heard of $E = mc^2$. If you want to understand that, you must know what mass is really like—the m in that relation is the difficult thing; the E and the c are comparatively easy to understand. If your work with force, mass and motion gives you a good clear idea of mass you will have learned something difficult and important.')

MEASUREMENTS AND KNOWLEDGE OF MOTION

Tape and trolleys All pupils should now use trolleys and tape-timers to look carefully at accelerated motion.

Class Expt 6 What stays the same? Constancy of acceleration

This is the essential beginning of our careful work with force, mass and acceleration. Although pupils have done this in an earlier year, we should encourage them to try it now with greater care.

Apparatus

8 to 12 dynamics trolleys ‡	item 106/1
8 to 12 timers	108/1
8 to 12 rolls of ticker-tape	108/4
20 elastic cords for pulling trolleys ‡‡	106/2
8 to 12 runways ‡‡‡	107
8 transformers for timers	27

‡ See the notes on equipment in *Teachers' Guide 3*.

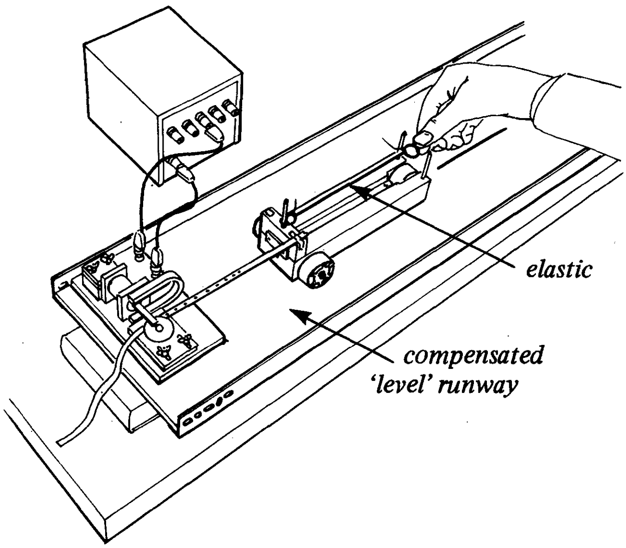
‡‡‡ It is essential to have a firm flat runway. There should be as many runways as the lab can accommodate. Ideally pupils should work in pairs. If more than four pupils have to share a runway, the experiment loses its value of learning for understanding by doing one's own experiment—drill replaces independent working and thinking. Also the experiment drags out in time as each pupil in turn takes his tape record.

‡‡ The elastic cords should be 15 to 20 cm long, stretched to a total length of about 30 cm when in action.

Preparation

Make sure by a test that the trolley wheels run freely and are well aligned. Start it with a push; it must run straight and far. (At the beginning of the year it is good to flush out old oil with solvent and apply a little new oil.)

Make sure the trolley boards are smooth and clean.



Install a stop at the finishing end of the runway to prevent damage to trolleys. A string, or a large rubber band acoss the end makes a good stop.

Compensating for friction Pupils will find that there is some trouble with friction but the idea of compensating for friction by a small tilt of the runway is not likely to occur spontaneously. Trying to extract it in discussion might take much time and even be frustrating. In any case, it is unnecessary in this first investigation—to see whether a constant force gives a constant acceleration—because friction will only reduce the constant applied force to a smaller constant resultant but, compensation is essential later on.

Procedure

Pupils follow these instructions:

* * * * *

Find out the way a cart moves as you pull it with a steady force along a flat road without friction. We call our cart with three ball-bearing wheels a 'trolley'.

Please be careful of your trolley's wheels. They are easily damaged by traffic accidents—then your experiment will be more difficult and less reliable.

To pull with a steady force, use an elastic cord with a ring at each end. *Stretch the cord the same amount all the time.* Put one ring on the post at the back of the trolley and pull the other ring to stretch the cord till the ring is just level with the front end of the trolley.

(If you prefer, put a pencil through the front ring and hold that level with the front posts on the trolley.)

Let the trolley start from rest. Pull it with steady force. Keep the cord at the same stretch as the trolley runs faster and faster—you may have to walk along with it; but it is easier to stand and sweep your arm with it.

At first this may seem hopelessly rough, but you will soon gain skill. Stand beside the runway, walk if necessary but do not run. (Or you may let your partner take charge of the timer and tape. For the start he holds the trolley still and gives a signal to you when he releases it.)

Take the tape that records your trip with the trolley. Let your partner have his turn at pulling. Each partner needs to make a tape of his own trip with the trolley.

Your tape and its chart. Cut your own tape into tentick strips. In trying to see what kind of motion the trolley had, you should use only the part of the tape for which you think you kept the pulling force fairly constant. You may have to leave out the beginning and end parts of the tape. In the good part of your tape, choose a clear dot near the beginning of the tape and mark that dot 0 (*not* 1). Count ten spaces along and mark dot 10, then dot 20, and so on. Cut your tape at those marks, so that you have a set of tentick strips.

The length of each tape strip is the distance travelled by the trolley in one tentick. So the tape strips show you *distances* travelled in *equal times*.

Obviously it is not the *distances* that are equal; it is the time that is the same for all strips—one tentick for each.

Make your own tape-chart by pasting successive tentick strips side by side on a sheet of paper, with their feet all on a straight line.

(If your tentick lengths are too long for the page when the trolley is moving fast, use fivetick lengths instead.)

In trying to see what kind of motion the trolley had, you should use only the part of the tape for which you think you kept the pulling force fairly constant. You may have to leave out the beginning and end parts of the tape.

Discuss the meaning of the tape-chart with your teacher.

* * * * *

Newcomers may still be doubtful about tape-charts. Give them help with a specimen, rather than let them lag behind.

Picture gallery Hold an exhibition of tape charts. Pupils often get encouragement and illumination by looking at each other's work.

Pupils survey the exhibits. Ask what the whole collection of charts seems to show about the motion.

ANALYSIS: OUTCOME OF PUPILS' EXPERIMENT 6

Praise for science: constancy When pupils have surveyed the picture gallery of charts, help them to look for a slanting *straight line* through the tops of strips—'an even staircase of steps'. Lead from that to the concept of *constant acceleration* for this motion.

Here is a simple, general fact of behaviour in Nature, exhibited by the charts or extracted from them. Its simplicity and general application deserve strong praise. This knowledge is a step forward in the progress of science.

The *constancy* of dv/dt contributes more to scientific understanding at this stage than a measured *value* of that acceleration. However, pupils who like mathematics may advance to that.

Calculating acceleration Now or later show interested pupils how to extract a measurement of acceleration from the chart.

[With a fast group mention the change of units ahead: *cm/tentick in each tentick* to *metres/second in each second* but leave that for some weeks yet.]

DISCUSSION FOR NEWCOMERS

Seeking constancy We hope newcomers will see an interesting constant characteristic in their tape-charts.

Suggest that, in science, we like to look for constancy in behaviour. We often begin by cataloguing the things *that stay the same*; then we feel sure of our knowledge and can use it.

Ask: 'What is it that stays the same in the trolley's motion as shown by the tape-charts?'

That is a difficult question for many newcomers because they do not know clearly that the length of each tentick strip is a measure of speed. To us it *is* the distance travelled in one tentick of time; but we know where we are going. A new pupil is not intent on looking for speed . . . changes of speed . . . acceleration. Help him by sketching an idealised chart (a straight line graph), and marking a staircase of gains on it.

Point out the horizontal time-scale—one tentick from each strip to the next—and leave that idea to brew. At this point the profile of vertical gains makes the easiest beginning—the horizontal progress from strip to strip is apt to grow more confusing if taught quickly.

Defining acceleration So far we have offered newcomers practical experience, but we have not rushed into a formal definition of acceleration. See Professor J. A. Wheeler's remark in his *Spacetime Physics*, quoted in the General Introduction.

Constant force: constant acceleration? Ask: 'What kind of motion did you get when you pulled with a steady force?'

KNOWLEDGE FOR ALL PUPILS

Encourage all to see that a *slanting* line shows increasing speed—we say there is 'acceleration'. And a slanting *straight line* shows speed *increasing at a constant rate* 'like pocket money rising by the same step every month, 5p a week *this month*, 7p a week *next month*, 9p a week *the next month* . . . .'

Constancies in behaviour are backbones in science—our assurance against insecurity. Since there *is* something that stays constant if the slanting line of tops is a *straight* line, we describe that something and give it a name. The *slope* of the line shows the gain of speed from one strip to the next, essentially $\frac{\text{gain of speed}}{\text{time}}$.

Since we want to name it *and* measure it we must know clearly what measurements to use and how to use them, to work out the interesting thing that stays constant—which pupils will see in any motion controlled by a constant force.

Our definition is operational, it becomes our way of calculating a; so we deliberately choose a definition that yields a constant value for those natural motions.*

Show how to extract a measurement of that acceleration from the tape-chart. It will be in *centimetres per tentick* gained *in each tentick*. (At all costs avoid, at this early stage, condensing the unit into cm/tentick^2—that would spoil the appeal to simplicity.)

---

* Galileo understood that necessity. He deliberated on measuring and naming dv/dt and dv/ds. He turned down the latter, giving an odd theoretical argument. A modern scientist would appeal to experiment and prefer to name and use whichever remains constant in common events like free fall—as the former does.

{**Alternative methods** Teachers may be tempted to vary the method of experiments and show other schemes for investigating accelerated motion. We suggest that elaborate demonstrations should be minimised because they compete disturbingly with class experiments. However, the multiflash experiments suggested for starting the year do give pupils an alternative look at constant acceleration.}

{It is obvious to us that changing from timer and tape to a strobe picture of a falling ball will not change the essential story of acceleration. But it would not have been obvious to the medieval scientists; and it is not obvious to many a pupil until he has had time to sort out the essentials from superficial details. The generalisation should be a delight for young people learning science: to share with Galileo the advance of distinguishing between essentials like velocity, force, distance and the non-essentials such as the colour of the trolley, or the use of a multiflash photo instead of strips of ticker-tape.}

{We also suggest a primitive measurement of acceleration with a scaler counting milliseconds from a pulse generator. In that we measure acceleration in terms of its basic definition, so the demonstration may help to dispel some doubts. And the method leads to interesting measurements such as the speed of a bullet, later on.}

MILLISECOND TIMING OF TROLLEY WITH SCALER

A direct measurement of acceleration It is good to estimate acceleration by measurements that fit directly in its basic definition:

$$\text{ACCELERATION} = \frac{\text{GAIN OF SPEED}}{\text{TIME TAKEN FOR THE GAIN}}$$

For this, make two measurements of SPEED, one early in the accelerated motion and one at a later stage. Then subtract to find the GAIN OF SPEED and divide that difference by the TIME between the two speed-sampling measurements.

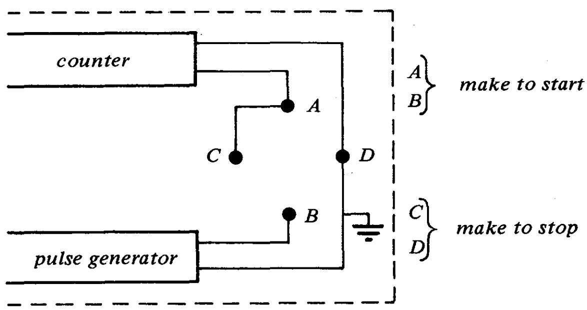
This may sound a complicated scheme for doing something relatively simple, and not doing it very accurately. Yet when pupils see it they recognise it as a basic way of measuring an acceleration by two separate measurements of speed and a measurement of the time taken to make the change of speed.

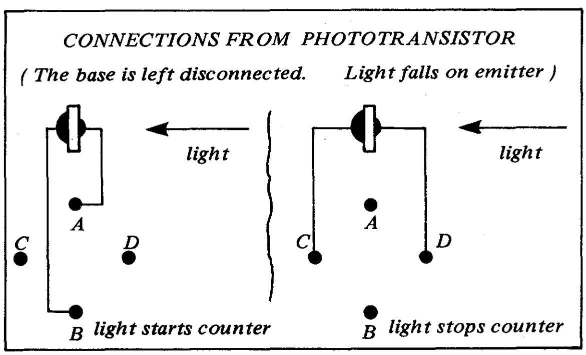
For each sampling of speed we need to clock the moving body's travel over a short distance—we must not use a long distance (or time) at each station or pupils themselves will object that the speed which we are trying to measure changes too much during the sampling.

Show this for a trolley coasting down a sloping runway. Use the length of the trolley as the speed-sampling distance and measure the time that the trolley takes to pass a fixed observation post. Arrange two observation posts, one near the beginning of the run and the other near the end, and measure the transit time at each. The transit times are likely to be a few tenths of a second—too short to measure with an ordinary stopwatch. (We could measure them with tape and vibrator, but that is just what pupils have already been doing.) We need a clock that measures milliseconds: the scaler does that.

To estimate the trolley's acceleration, we also need the time it takes to travel from one station to the other. Measure with a stopwatch operated by hand. (To try to measure *that* time by the scaler would be to misunderstand this rough experiment, which only uses the scaler to estimate the short transit times. A crude measurement of the total time between stations will suffice to give the same order of accuracy.)

CONNECTIONS INSIDE SCALER (simplified)





Demonstration 7 Basic estimate of acceleration with a clock that ticks 1000 times a second: use of scaler

AIM: To use a different instrument to estimate acceleration in terms of its basic definition.

This gives some pupils a clearer feeling for acceleration.

Apparatus

1 scaler	item 130/1
2 photo-transistors with light sources	130/2
1 dynamics trolley	106/1
1 runway	107
1 card	
1 stopclock (or stopwatch)	507
4 retort stands, bosses and clamps	503–506

For details of the operation of the scaler, see Appendix 4.

Method

A trolley carrying a card runs down a sloping runway. The scaler is set to count millisecond pulses. The counting is switched on during the time light directed to a photo-device is cut off by the card on the passing trolley. Thus the scaler records the time-of-transit of the card-length past the photo-device. That record in milliseconds and the length of the card together yield an estimate of the trolley's speed at that station.

Two such speed-sampling stations are set up, one near the beginning of the runway, the other near the end. Thus we can calculate the trolley's speed at each station and thence its *gain* of speed.

The overall time of travel between stations (the time taken to make that gain of speed) is measured separately with a stopclock or watch.

Then the acceleration is estimated as:
[GAIN OF SPEED]/[TIME TAKEN FOR THAT GAIN]

Preparation

Attach a card 10 or 20 cm long, and 5 or 6 cm high to the trolley.

Raise one end of the runway on books or wood blocks to give it a slope about 1 in 20. Put a support under the middle of the runway if there is any sign of sag.

Place photo-devices at two speed-sampling stations, one about $\frac{1}{2}$ metre from the start, the other $\frac{1}{2}$ metre from the lower end where the trolley has to be caught.

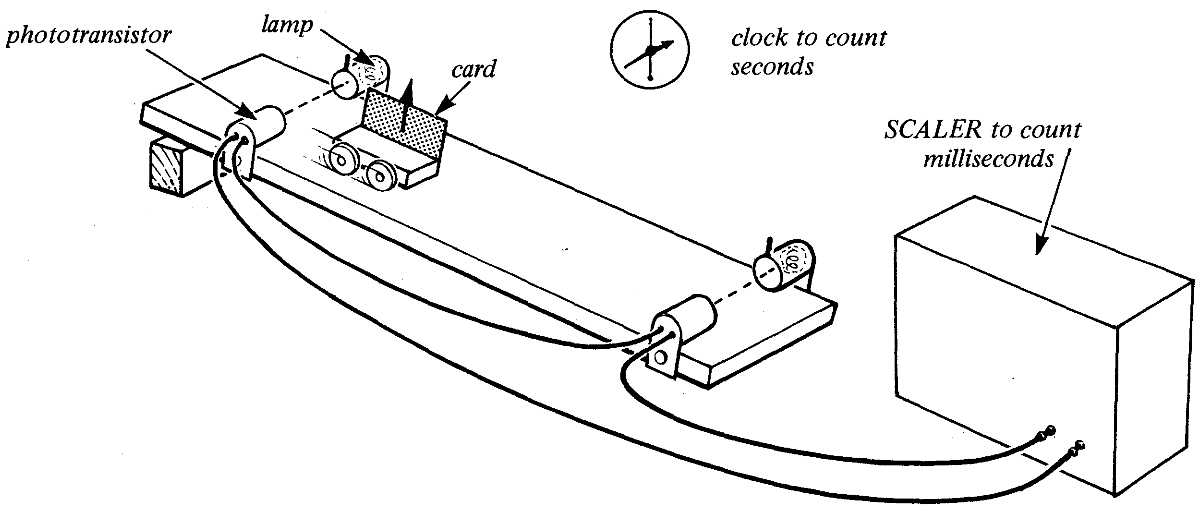
Connect the two photo-devices in series and connect the pair to the 'make-to-stop' terminals of the scaler. Light the two small lamps—there is usually a supply for them on the back of the scaler—and place each about 20 cm from a photo-diode. Direct the light in carefully. (It may be necessary to shield the photo-device from other light.) When the device is strongly illuminated it has low resistance and acts as a switch to stop the scaler from counting. If the light reaching *either* device is cut off this becomes an open switch; and the scaler counts the time during which the illumination is obstructed.

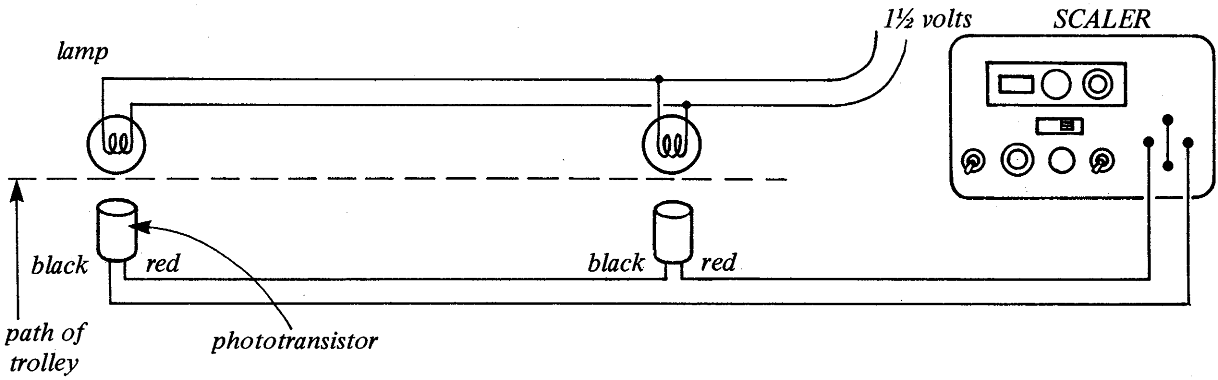
Make sure the card on the moving trolley cuts off the light while the trolley is passing each station. Then the scaler will count the number of milliseconds that length of card takes to pass by.

The trolley should carry some mark at its mid-point for the overall timing from station to station. (Strictly, we should take the time between mid-*times* during the samples, rather than mid-*point* positions; but that is difficult and unnecessary in this teaching experiment.)

Procedure

Explain the arrangement for sampling speeds, and show some sample runs. Explain that each speed will be given by LENGTH OF CARD/TIME-OF-TRANSIT. (Each will really be an *average* speed, since the trolley is accelerating even during the sampling.)





For measurements: release the trolley at the top of the runway. Read the scaler at both stations in the same run. Post some good pupil observers to read the scaler quickly after the trolley has passed the first station. (There is a re-set switch on the scaler, but it is easier to leave that alone, read the dials after each station, and subtract.)

Measure the overall time the trolley takes to travel between the two stations with an ordinary clock, not with the scaler. (It is better not to give pupils individual stopwatches. That would divert attention from the scaler.)

Estimate $(v_2 - v_1)/t$

Details of the scaler used as a millisecond clock

Schools using the Nuffield programme will have a scaler (Panax or similar) which has a built-in pulse generator giving 1000 pulses a second. The scaler is simply an electronic counting device which counts small pulses of electric charge or voltage fed into it and registers the total visibly. It is the 'counter' of a 'Geiger counter'. It can easily be converted into an electronic clock—one of the two essential ingredients of every clock is a counting device, to count swings of a pendulum or the cycles of alternating current, etc.

When we use the scaler as a clock we do not need the built-in high voltage supply for Geiger tubes. But we do need a source of regularly spaced pulses for the scaler to count, and a suitable switching mechanism. These are equivalent to the balance wheel of a stopwatch and the control button. The frequency of the pulses can be checked against an ordinary clock.

On their way from the pulse generator to the counting mechanism, the pulses can be brought out to an external switch and back, so that they are not counted unless the switch contact is made. There are also connections which stop the counting as long as another switch is closed—as if that switch short-circuited the pulse generator. Some modern scalers for school use have extra internal switching to make them still more versatile. Consult the maker's instructions.

Thus the scaler can count the time, in milliseconds, between two switching events, each of which may be the closing of a switch or the opening of a switch.

The switches may be knife switches or other metal contacts, or they may be solid state devices such as photo-transistors, which have a low resistance when illuminated and a high resistance in the dark.

THE PHOTOSENSITIVE DEVICES FOR SWITCHING Some early scalers were supplied with germanium diodes; nowadays better silicon photo-transistors are used. Since the type of photo-device and the labelling of switch terminals vary from one maker to another, the advice is 'follow the manufacturer's instructions'—though careful trial and error may be better still. (At all costs avoid cadmium sulphide photo-*resistors* which are notoriously slow and uneven.)

Since d.c. pulses from the scaler travel through such a switching device, it is essential to connect it to the scaler the right way round—best found by trial.

DISTANCE FROM LAMP TO PHOTO-DEVICE The brightness of the little lamp changes with age; also some lamps incorporate a lens, and others do not. Find the optimum distance by trial.

Pupils who are interested and have time to spare might try a quick experiment with a case of *changing* acceleration. That would anticipate a warning which will be given later: that acceleration does not have to be constant—in fact many motions in nature have changing acceleration.

Class Expt 8 Acceleration that is not constant *(BUFFER OPTION FOR FAST PUPILS)*

Apparatus

Each *pair* of pupils will need the following:

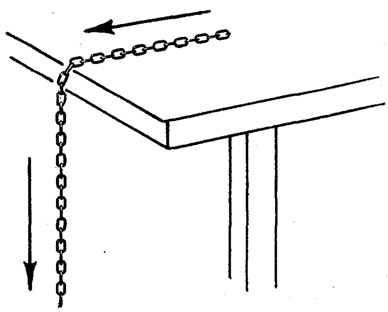
1 length of chain (about 1 metre long)	
1 timer	item 108/1
1 transformer for timer	27
tape	108/3 or 108/4

Procedure

Pupils follow these instructions:

* * * * *

Lay a length of chain on a smooth table, stretch it out at right angles to the edge. Pull the end a little way over the edge until, on release, the whole chain slides. Then the hanging portion pulls the rest with increasing acceleration until it is all falling freely. Watch the motion.



To obtain a record, arrange a timer so that the upper end of the chain on the table pulls the tape through.

* * * * *

Notes

1. The chain must be stretched out across the table. If it starts in a loose pile at the edge of the table then the motion is one with constant acceleration, $\frac{1}{3}g$.
2. The bob of a long pendulum will make a tape-record of changing acceleration.

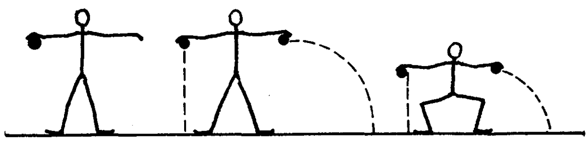
FREE FALL

Before proceeding to Newton's Laws, let pupils examine and measure the motion of free fall.

In Year 3 pupils should have compared the free fall of small and large dense objects—using fingers, not gadgets, for simultaneous release. If any missed that, or are still doubtful let them try it now.

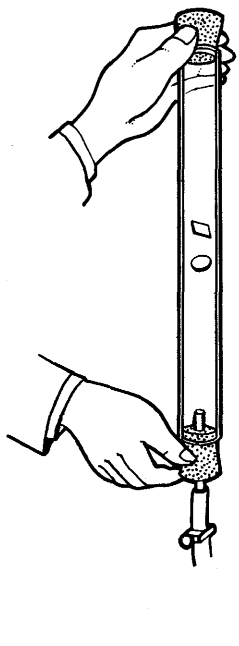
Class Expt 9a Dropping objects

Each pupil holds unequal dense masses in outstretched hands and releases them.



listen for simultaneous arrival

Then each pupil releases a scrap of metal or stone and a scrap of foamed plastic or paper. Ask for suggestions concerning the difference. Those who have not tried a guinea-and-feather experiment themselves should try it now. This is worth the time, for personal experience.



Class Expt 9b The guinea-and-feather experiment

Apparatus

1 vacuum pump	item 13
1 metre pressure tubing	563
1 connecting tube (glass or brass)	
8 tubes for 'guinea-and-feather' expt	110
8 Hoffmann clips	522
8 short pieces of rubber tube to carry the clips	
8 small coins	
8 scraps of plastic foam	

The tubes are about 60 cm long, 5 cm in diameter; one end is closed with a plain rubber bung; the other end with a bung carrying a tube to take a short rubber tube with clip. Pressure tubing from the vacuum pump carries a short connecting tube to fit the short rubber tube while the pumping is done.

Pupils work in groups of four—a larger crowd for economy would spoil the sense of personal experience.

Procedure

Pupils follow these instructions:

* * * * *

Put a small coin (or other piece of metal) and a scrap of plastic foam in the tube. Close the tube with the rubber stopper.

Take it in turns with your partners to hold the tube upright and turn it upsidedown quickly. Watch the two falling objects.

Then bring your tube to the vacuum pump and have the air pumped out. Listen to the pump—you can hear the air being ejected in decreasing amounts. Seal the tube with a clip on its short rubber tube.

Again take turns at turning your tube upsidedown.

Then let air in again and try once more—this may be your best chance of seeing how great the difference is.

* * * * *

Is there constant acceleration in free fall? Some pupils may have already investigated the motion with a series of stones tied on a string; but most have only a general idea. Now is the time for a quantitative test.

When pupils have become familiar with $s = ut + \frac{1}{2}at^2$ (Chapter 1A) and can use it with confidence—knowing that it only holds for constant acceleration—they should use it for a simple test of constant acceleration in free fall (Expt 10). It is an experiment that they might try at home.

Pupils reverse the logic from 'if a is constant $s \propto t^2$', to 'if DISTANCES are proportional to TIME^2, then the motion has constant acceleration'.

Or pupils may do a preliminary experiment, Expt 9c, to discover the square law (distances 1:4:9 ... at times 1:2:3 ... from start), by measuring 'total' strips.

† Preliminary Class Expt 9c A different exhibit of tapes: total distance versus time *(OPTIONAL)*

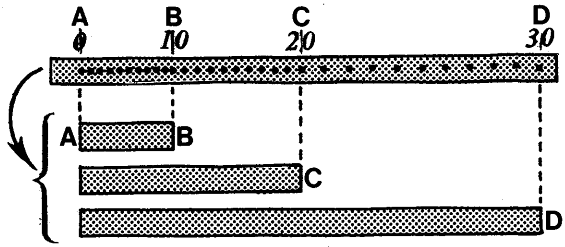
Apparatus

8 to 12 runways	item 107
8 to 12 trolleys	106/1
8 to 12 timers	108/1
8 to 12 rolls of tape	108/4
8 transformers	27

Procedure

Pupils let a trolley run down the incline as before, making a tape record of its motion. *They take special care to start the vibrator at the instant the trolley is released.* One partner keeps his finger pressing on the vibrator blade until he releases the trolley.

Each pupil makes his own tape. He marks his tape clearly at every tenth dot, thus marking off tentick lengths, *but he does not cut it up*. Then from a fresh supply of tape he cuts 'total strips': a length equal to the travel in the first ten ticks, then a length equal to the *total* travel in the first 20 ticks from rest, then the *total* travel for the first 30 ticks and so on.



new 'total' strips, starting from rest

Ask pupils to look at these new '*total strips*', each of which gives 'total travel from rest' and see what they can find out. Tell them there is a number secret among the lengths.

The lengths of tape will soon grow huge in this, and the chart that a pupil makes will have to be a temporary one of tapes laid on a long table.

Give pupils a helpful start by suggesting that they use the first strip (for one tentick from rest) as a measuring stick for the others.

Class Expt 10 Testing free fall *(Possibly a good HOME experiment)*

Apparatus

string and stones

Procedure

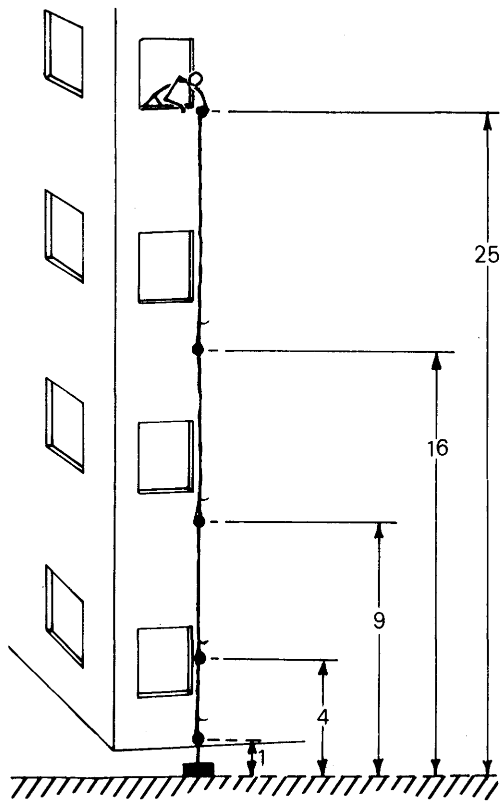
Pupils follow these instructions:

* * * * *

Go to a window high above the ground. Take with you a long string that will reach from your hand down to a brick resting on the ground. Tie small stones or weights to the string 1 metre above the ground, 2 metres, 3 metres .... To make sure the sounds are sharp and audible, place a sheet of metal on the ground.

Hold the string taut and let go. While everybody listens to the stones hitting the ground you will hear evidence of acceleration like this:
bang......... bang .... bang .... bang . bang
To make sure the sounds are sharp and audible, place a sheet of metal on the ground.

Now try the experiment again but tie the stones on at different distances, chosen so that *if* the *acceleration of fall is constant* everyone will hear the bangs as a regular series equally spaced apart.



For that you have the brick at the ground (zero). Tie the first stone one quarter of a metre above the ground. How many quarters of a metre above the ground should you tie the next stone? How far for the next? You will need to calculate the distances for the stones from your knowledge of constant acceleration. Then you will be making a prediction which you test when you let go of the string.

* * * * *

Measuring the acceleration of free fall

{Measuring *g* was a heavy tradition in physics teaching earlier this century but it was often more interesting to teachers than to pupils. Pupils now have stronger interests in such things as atoms and energy; and in a Nuffield Physics class they are not likely to enjoy watching someone else measure *g*.}

{Nevertheless the constant acceleration of free fall is surprising and important and if pupils make some quick measurements they will enjoy it and be impressed to find that they can all agree fairly closely with each other. If we labour the measurement we shall spoil things at this stage. We should be careful not to over-emphasise a need for accuracy, by following the tradition of earlier times when measurements of *g* were considered specially good training and were in fact needed for engineering and other purposes.}

{The acceleration of a freely falling body is as important a thing as ever—in geophysical prospecting, engineering and rocketry—so pupils should understand what it is and should have the experience of measuring it. But if they need a very precise value they can obtain it from other people's work. If precise measurements of *g* were something that pupils could carry out easily and well (and thus achieve a great sense of success in precision) we should probably urge it on all teachers; but the only available methods for high precision are pendulum ones, which do not give pupils their result of *g* by a fully understood route, as we have to supply a formula without much support.}

{Even the formal claim that nevertheless pupils should try the pendulum measurement, since it is the ultimate standard used by professional physicists, is put out of date by the fact that the most precise measurements of *g* are now being made on freely falling objects! They use an interferometer with electronic frequency measurements for timing.}

Pupils should measure *g* by some method that gives an answer that can be trusted within a few per cent, a method they feel they understand perfectly. But before that they should make a rough, simple estimate.

Class Expt 11 Rough estimate of *g*

Apparatus

16 stopwatches ‡	item 507
16 metre rules	501
16 stones or other objects to be dropped	

‡ For this estimate, which is meant to be very rough, a clock that gives a tick every half second would be better still.

Procedure

Each pupil times a fall, if possible of several metres; and calculates *g*, to *one* significant figure.

Then give a good measurement with the scaler as a millisecond clock.

A good use for the millisecond scaler clock: measure *g* A large steel ball is allowed to fall a few metres from rest. The scaler measures the time of fall and the acceleration is calculated from $s = \frac{1}{2}at^2$.

This is a very good demonstration, if the scaler is a familiar object in the teaching; but it is a bad demonstration—for our purpose of well-understood physics—if the scaler has to be brought out specially and carefully adjusted and presented as something strange. So we urge teachers to explore the uses of the scaler at an early stage.

This may be a single demonstration or better, a class experiment in which the teacher sets up the arrangement and then each pupil in turn makes his own measurement. As a class experiment, this should be done quickly for the fun of measuring *g*. Pupils should not try this until they have some confidence in the relation $s = \frac{1}{2}at^2$. It should not be an experiment that drags the relation in as a mysterious 'formula', simply to get the answer. Nor should it turn into a whole series of measurements to 'get a good average', or tediously to explore the relationship between height and time of fall. At this stage, teachers and pupils should be anxious to get on to new topics in dynamics and it would be sad to delay progress by developing an enthusiasm for a set of measurements that would not have a very important outcome.

DESCRIPTION OF APPARATUS: SCALER TO MEASURE FREE FALL

FALLING OBJECT: metal ball; e.g. steel ball, diam about 2 cm.

CLOCK: a scaler which has a built-in pulse generator giving 1000 pulses per second. These pulses can be brought out by wires to external switches and carried back to the scaler to be counted, so the scaler acts as a clock, registering milliseconds on its dials. (See the earlier use of the scaler in a simple measurement of acceleration.)

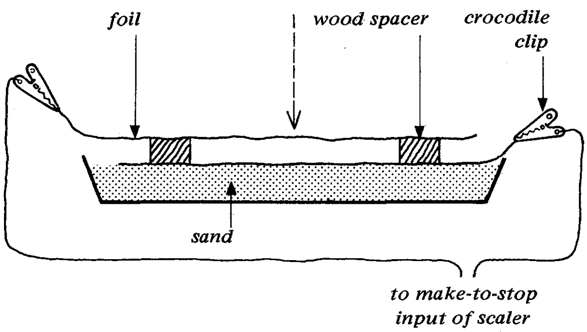
STARTING GATE: an assembly of three metal pegs fixed on an insulating block so that the ball can be held up against them. The ball, making contact, completes a circuit through two of them to hold the millisecond clock stopped. This simple arrangement is better than an electromagnet release mechanism which may introduce time delays. (If an electromagnet release must be used, place a scrap of paper between the ball and magnet core, to minimise delays. With an electromagnet there are difficulties in arranging for the simultaneous switching of the scaler so we do not recommend an electromagnetic release, tempting though it sounds.)

SCALER: the scaler, driven by its 1000 Hz pulse generator counts milliseconds from the instant the ball leaves the pegs till the ball arrives at the stopping switch.

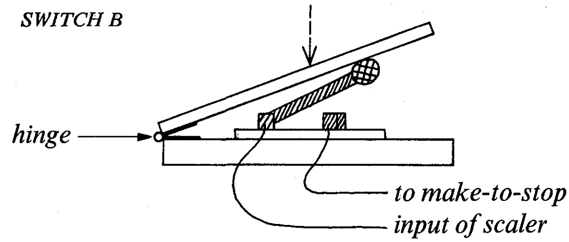
STOPPING SWITCHES:

SWITCH A The ball stops the scaler-clock by pushing two sheets of aluminium kitchen foil together to join the scaler's *make-to-stop* terminals again.

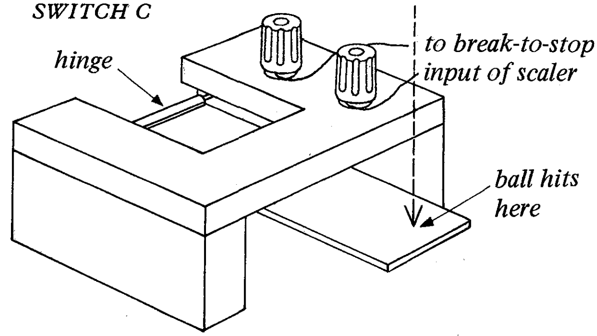
SWITCH A



SWITCH B



SWITCH C



Place a tray of sand on the floor. Lay a sheet of aluminium kitchen foil on the sand; then two strips of wood on top of the foil; and another sheet of foil on top of the wood. When the ball arrives it smashes the two sheets of foil together. The sand prevents bouncing.

ALTERNATIVE SWITCHES B AND C are less satisfactory.

SWITCH B The ball hits a hinged platform which closes a knife switch to stop the clock. (A micro-switch would work well, but a simple knife switch is better because pupils can see how it works.)

SWITCH C A trip-switch is arranged so that the ball *breaks* a circuit when it arrives. This switch must be connected to the scaler's *make-to-start* terminals. When the ball strikes it, the switch opens and the scaler stops. That may be confusing—the teaching is probably easier if the arrival switch works the same way as the starting switch; that is, if the clock starts on a 'break' and stops on a 'make'.

Demonstration or Class Expt 12 Measuring *g* with scaler as a clock

Apparatus

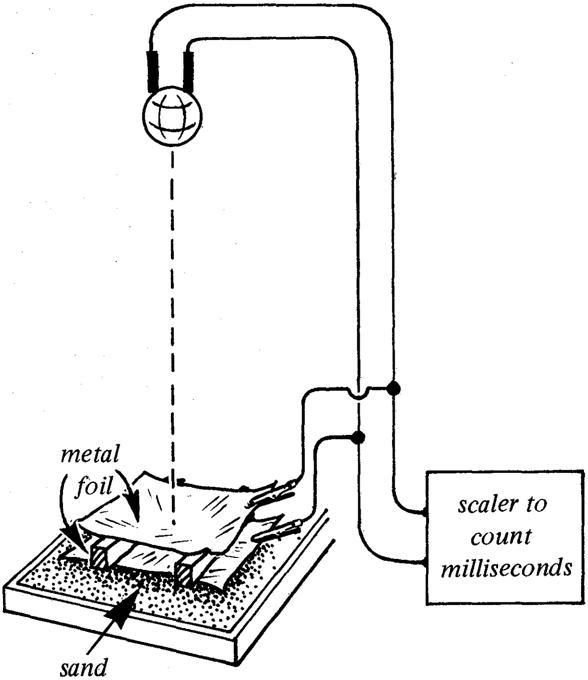
1 scaler	item 130/1
1 ball-bearing ball	131A
1 starting gate	131H
1 trip-switch	131I
1 retort stand and boss	503–505

Procedure

For details of the use of the scaler as a timing device, see Appendix 4.

Hold the steel ball up against the three-peg assembly. Connect two of the pegs to the *make-to-stop* terminals of the scaler. The ball completes the circuit to keep the clock stopped, until it starts to fall.

(It is easier to hold the ball by a string which is released from above.)

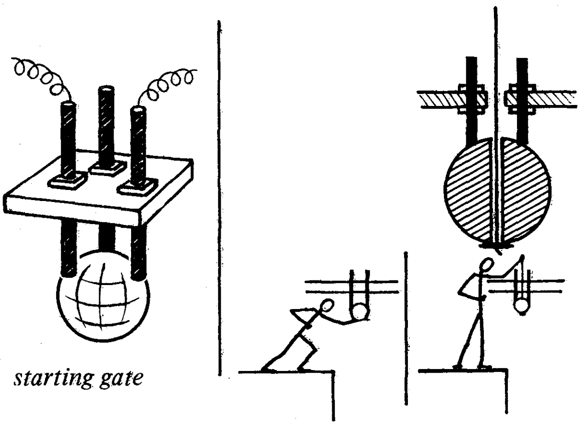


When the ball is released the scaler starts.

After a measured fall, the ball stops the scaler by hitting a switch (type A or B or C—see Box).

If pupils are to take turns at making measurements, a switch of form B is best, because it can be re-set quickly.

Pupils calculate g, assuming the ball started from rest.



If there is danger of electric shock, the ball must be held by string threaded through a hole in it or attached to a hook on it.

Multiflash picture for *g* If a multiflash picture was taken of a freely falling object, earlier this year, pupils may ask whether they could obtain an estimate of g from that. The answer depends on the records made then. Was a centimetre scale included in the photograph? Was the frequency of flash exposures recorded? If the record is complete give copies of the picture to pupils for an optional measurement.

If the scales of distance and time were not recorded it is doubtful whether a repetition of the whole experiment is worthwhile now.

Ready-made copies of multiflash pictures To distribute printed copies to pupils who have never seen a real multiflash experiment carried out would be confusing and a bad mistake in our teaching. In spite of obvious economy, we hope that no school in the Nuffield Physics programme will be tempted to do that. However, if pupils took part in a real multiflash experiment, they should be ready to use printed copies (even of someone else's picture) without much confusion or damage.

{**Second-hand evidence** Again and again in each area of natural science, we all of us have to receive second-hand evidence, review it and accept it with only moderate reservation. But we should not accept such evidence unless we understand clearly how it was obtained and feel that we have some knowledge of its reliability.}

{In the case of multiflash pictures, one might expect pupils to be prepared to accept someone else's picture which they did not see taken, but at this stage that would come with too strong an atmosphere of assertion—who could know what choosing or retouching of pictures there had been?*}

So even if pupils saw the original demonstration, we do *not* advocate giving them copies to analyse unless those are made from the actual experiment they saw.

* Compare this danger with that of computer teaching being programmed with hoped-for but mistaken science.

Class Expt 13 Estimating *g* from the multi-flash picture *(OPTIONAL)*

Procedure

If a centimetre scale was included in the demonstration at the beginning of the year, and if the strobe frequently was recorded, make copies of that picture which pupils saw taken and give one to each pupil. For copies *either* make photographic prints (see Appendix) *or* project the negative on a large sheet of paper, mark up the image on the sheet, then make copies of the sheet.

Pupils follow these instructions:

* * * * *

On a print of the multiflash picture, mark the successive positions of the falling object clearly. (Where the ball was falling fast its picture may look drawn out into a blur. If so, mark a 'half-way' point on the blur.)

Measure the *total* distance of fall from the start to each mark. Plot a rough graph of total distance against time. You will see that the graph line must be a curve. *What could you plot instead, with hopes of a straight line?*

If the motion has constant acceleration, $s = \frac{1}{2}at^2$ for fall from rest. So you should plot distance s against . . ? . . Try this. Then the graph will tell you whether the motion did have constant acceleration.

Instead of that, you might assume you know the type of motion and just calculate acceleration from one measurement of your photo. That would be quicker, but less of a scientific investigation.

* * * * *

Special experiments for measuring *g* Many ingenious schemes have been suggested for measuring g with simple apparatus, such as a swinging pendulum that hits a dropping ball, or a rotating gramophone turntable that catches a falling dart. In general, these are to be avoided here because the ingenuity of the method is likely to swamp the essential sense of measuring something.

An important exception Where a teacher has invented and constructed his own special device for measuring g, he should certainly use it with his own class. The sense of research, which is transmitted unconsciously to his pupils, is of enormous value in giving them a true sense of science. Yet here, as elsewhere in the programme, other teachers should hesitate to adopt someone else's special scheme—however ingenious and successful—unless they are satisfied that it will not delay the progress and that the essential measurement will shine through the details of the operation of the apparatus.

WEIGHTLESSNESS

Nowadays most pupils have ideas about 'weightlessness' from pictures and stories of astronauts; but there are still some misconceptions, perhaps partly due to the continuing confusion between mass and weight, partly due to an air of strange magic which invests some popular accounts.

Once pupils see that what we may call 'weightlessness' is an extension of the simple story of freely falling bodies, arguments will calm down and magic can disappear—though wonder at the general property of nature should not disappear.

Pupils' Text has a 'thought experiment' which may help pupils to clear these ideas.

Space travel The questions of 'weightlessness' in a satellite or rocket will crop up. We must meet it fairly every time it is raised. The question is partly one of fact and partly a semantic one.

The fact In a satellite, or in an ordinary lift falling freely, not acted on by forces other than gravity, all objects *appear* to have no weight. Something placed in mid-air will just float there.

(If the lift's cable is pulling it, if the satellite is encountering air resistance, or if its rocket's motor is blasting, there *is* another force, and objects inside will *not* appear to be completely 'weightless'—though their 'weight' may seem to take a peculiar direction.)

Wherever gravity alone acts, all objects are pulled by forces that are proportional to their masses as shown by the Leaning Tower experiment that Galileo did not demonstrate publicly, or by Newton's guinea-and-feather experiment. They all fall with the same acceleration. Therefore inside the satellite, etc., any object that is given some motion just keeps it (Newton's Law I) and any object at rest relative to the satellite just remains so.

Since the Earth is a satellite of the Sun, we never notice the Sun's pull on us, because, like all our surroundings, we are falling towards the Sun with an acceleration which keeps *us* in the same yearly orbit as all the rest of the Earth. Except, that is, for minor effects due to differences of distance from the Sun between different places on the Earth. These tiny differences build up the Sun's contribution to great ocean tides.

Local effects in a satellite Of course, a large enough satellite will reveal local differences inside; and a long enough time might reveal tiny local gravitational attractions between bodies inside. Both these effects will seem natural enough when the time comes—all the easier to understand if we do not mention them now.

The semantic question What is the meaning of 'weight'? Does that word mean the pull of the Earth *as seen by an outside observer*, or *as judged by an inside one*?

Children with a hard-headed common sense view aided by newspaper articles and encouraged by a love of romance, may incline to the latter view and then claim 'true' weightlessness in a spacecraft. There is nothing wrong with that except that we should then have to be careful to word our dynamical statements to conform with that choice.

However it will probably make our teaching clearer if we make the former choice and say:

'WEIGHT is the word we shall use for the pull of the Earth (and Sun, etc.) which *always* acts on any mass. If you are busy measuring that pull on a brick with a spring balance and you jump out of the window and fall, then you and the spring balance and the brick will all fall together.

Remember the guinea-and-feather experiment.

During your fall you could unhook the brick from the spring balance and leave it to fall beside you. Except for air resistance slowing it (or you) both will fall together. You can avoid some of the effects of air resistance by climbing into a big box and arranging to let that fall freely. Then inside the box, everything will *seem* to have no weight. We shall say things have no *apparent* weight.'

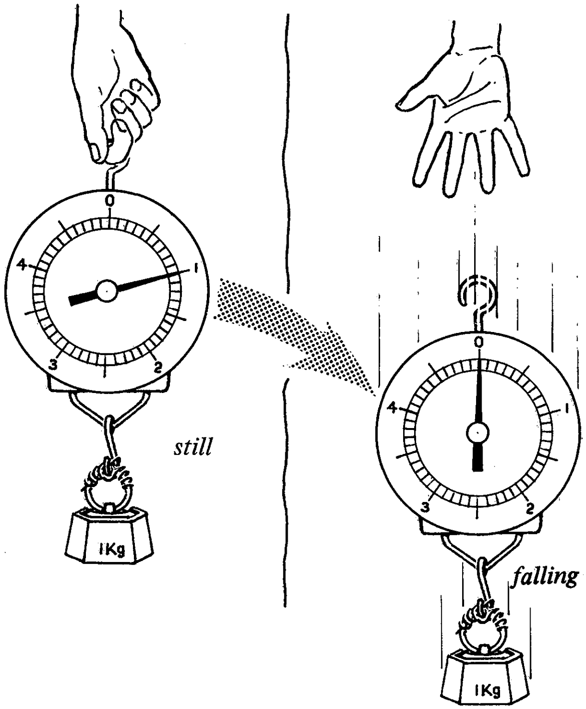
We suggest that teachers should clarify the *factual* story by going over it again every time a question arises, but ask pupils to compromise on the *semantic* story by using the word '*apparent*'.

Experiments to illustrate 'weightlessness' The usual demonstration of letting a spring balance carrying a load fall freely is dishonest unless the load is firmly anchored to the balance. The spring inside the balance causes trouble.*

---

* Whether the load is hung on a hook and stretches a spring, or is placed on a kitchen scale and compresses a spring, *the spring is distorted until the release.* On release the load becomes apparently weightless, but its mass is still there and is acted on by the force of the distorted spring. The load accelerates upwards (with an initial acceleration g). Unless the load is wired onto the balance, they part company and never meet again till they crash on the floor.

Demonstration 14 'Weightlessness'



Apparatus

1 spring weighing scale	item 216
1 kilogram	32

Procedure

Attach the kilogram very firmly* to a large spring balance and show the reading. Put a cushion on the floor. (Or ask some pupils to hold a blanket to catch the apparatus.) Let the balance with the kilogram attached drop.

Pupils watch the balance while it is dropping.

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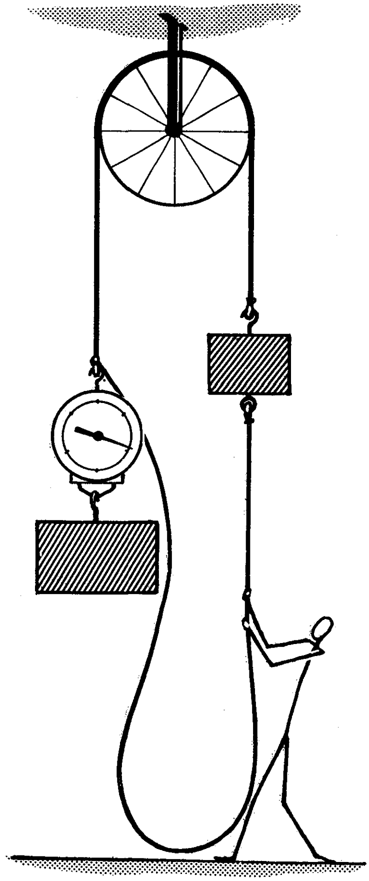
* Only if the load is firmly wired to a *strongly damped* balance can one see an honest and convincing demonstration.

A partial demonstration Honest experiments to show *partial* 'loss of weight' when an object is falling with acceleration less than *g* are easy to arrange, but not convincing except to a sophisticated observer who will extrapolate.

Demonstration 14X Partial 'Weightlessness' *(ADVANCED, OPTIONAL)*

Procedure

Install a large pulley that has little friction near the ceiling. Run an endless loop of cord over it. Attach a spring balance carrying a load to the cord on one side. Attach a counterpoise which is less than the total of (load + balance) on the other side. Pupils watching the spring balance in free motion will see it reading less than the full weight of its load in equilibrium. (The endless loop makes the accelerating system easier to control, the counterpoise ensures a suitable acceleration, but the reading of the spring balance is all that has to be seen and understood.)



CHAPTER 1A

HELP WITH USEFUL MATHEMATICS AND METRIC MEASUREMENTS

Chapter 1A in Pupils' Text is optional. It is like an appendix, which pupils may draw on for help if they wish

FORMULAE: BOTTLENECK OR AUTOMATIC GEAR-CHANGE?

We shall offer some formulae relating to motion with constant acceleration; and some pupils will use them with pleasure. Could we increase the number of happy users? If formulae are disliked, or algebra is feared, pupils are slowed up in calculations of free fall; practically cut off from understanding K.E. $= \frac{1}{2}mv^2$; and completely stopped from enjoying Newton's magical production of Kepler's Law III or J. J. Thomson's great measurement of electrons.

Yet our uses of formulae in O-Level physics are simple: as mementos (little more than mnemonics), as shorthand to express relationships with economy, and as reliable machinery to take the place of long verbal arguments.

A person who can learn ordinary shorthand could learn algebra quicker—that is, the algebra we need and use. We never need the clever methods and deeper insight that are essential to professional mathematics—and to modern theoretical physics.

Formulae for accelerated motion In *Pupils' Text*, a short, *optional*, Chapter 1A offers to show pupils how to construct traditional formulae such as $s = ut + \frac{1}{2}at^2$. We approach that development by saying that our use of letters instead of numbers is just shorthand* thus hoping to catch the fancy of some who might otherwise maintain an inhibiting fear of using mathematics.

{In this matter of using algebra and trying to dispel fear of it—so that more pupils can succeed with early stages—it is not a question of whether one can get to the end of accelerated motion, or kinematics or Lagrange's equations, or life itself—it is whether pupils can *enjoy getting some of the way with a sense of success to encourage understanding.*}

{In brute pragmatism, we suggest it is worth while for some pupils to get just as far as $s = \frac{1}{2}(v + u)t$; others as far as $s = ut + \frac{1}{2}at^2$, while some reach K.E. $= \frac{1}{2}mv^2$ and know how they got there. Note that, in this little sequence, the first can in practice easily be kept at an arithmetical stage with numbers and no symbols, while arriving at the last threatens to lose meaning and usefulness without algebra or geometry.}

{Pupils with less mathematical interest will find, as substitutes, intriguing experiments ahead.*}

For those who will welcome algebra and use it, optional Chapter 1A offers encouragement and practice.

Starting with a definition of constant acceleration, we arrive at several useful rules or

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* We must, of course, be careful to safeguard the proper reputation of mathematics by explaining that it is only at this early stage of practical use that one might treat algebra as 'just shorthand'.

* We are concerned, on behalf of many pupils, with understanding of physics; but only some of our physics involves mathematical reasoning. O-Level candidates who avoid that reasoning and choose more experimenting do not necessarily cut themselves off from examination success.

formulae. We trust teachers will make it clear to pupils that such formulae are only superficial devices for economy, not the heart of physics.

In any public examination on this form of learning physics, pupils should expect to find any such formulae printed on the examination paper. So they should not regard these formulae as mysterious keys to be learnt by heart; and they should only pursue the derivations in this chapter if they find them sensible and interesting.

USING GRAPHICAL APPROACHES TO FORMULAE FOR MOTION

Let pupils see that the area under a graph of SPEED plotted against TIME tells them distance travelled. Then sketches of graphs can lead them to formulae with valuable insight.

Pupils see that the graph line must be a straight line if the acceleration is constant; then they see how a variable acceleration would upset the simple result—so this method is almost as good as the calculus derivation concealed in it.

Looking ahead to Chapter 5 where we offer to show that kinetic energy is $\frac{1}{2}mv^2$, we use another graph; a graph of v (plotted along) and mv (plotted upwards). That graph is *necessarily*, whatever the motion, a straight line of slope m (until relativity changes are noticeable). We show pupils that the area between the line and the mv-axis tells them the motion-energy given to the moving body. And that area is $\frac{1}{2}mv^2$. Thus pupils obtain K.E. $= \frac{1}{2}mv^2$ without having to assume constant acceleration.

(A keen sophisticate can even find $E = mc^2$ by a rough-and-ready extension.)

However, many beginners find the automatically-straight graph strange—'not a proper graph'—so it may be helpful to offer a similar graph as an introduction. Defining π by saying that the circumference of a circle is $2\pi R$, we plot a graph which shows that area $= \pi R^2$.

A DIGRESSION: S.I. UNITS

Pupils' Text also discusses metric units and the S.I. choices.

{**Modern measurements** Long ago, formal physics courses often started with definitions or statements of units. We have come to regard that as a dull beginning: pupils did not welcome it as an obvious necessity; they were not even sure it was science. Yet now, with changes to metric units proceeding at uneven rates—and often lagging with older people at home—some class groups may find a quick survey or exhibit helpful. We do not suggest that as a formal lesson, but only as a brief demonstration and an exhibit to be kept on one side in the lab for a while.}

Although we support the move to metric units wholeheartedly, we retain some decimal subdivisions and multiples (e.g. centimetres, milliamps, kilometres) where we consider the use of those will help beginners to find physics nearer to common sense.

Expt X Metric measurements
(OPTIONAL: OMIT OR POSTPONE UNTIL NEEDED)

Apparatus

16 metre rulers (or 1 ruler and 16 metre tape measures)	item 501 (or 33)
16 1-kilogram masses	32
1 transparent box 10 cm × 10 cm × 10 (or 11) cm high inside	
or Metric Aid box 10 cm × 10 cm × 10 cm	10D
1 kitchen weighing scale (or an equal arm balance)	
1 cardboard metre cube ‡	223

‡ This cube of cardboard sheet, with hinges at edges so that it can fold flat for storage, will prove more important than one would expect. The trouble of making it will be justified by its help in dealing (later) with the density of water in S.I. units.

Procedure

a. Show a metre ruler. Ask every pupil to write down his or her height in metres and in cm, (by guessing, unless already known). Then offer metre rulers for a quick direct measurement.

b. Offer a kilogram to each pupil. At this stage most will feel its weight—an unfortunate diversion from the real use of a kilogram as a unit of mass. Nevertheless it is better for pupils to feel that force if they are not yet sure how it compares with the weight of a pound. Soon there will be a 'mass exhibit' of a kilogram sliding on a table covered with small balls to reduce friction, so that pupils can push the kilogram and feel its inertia.

If pupils do not know their mass in kilograms, ask them to find out. (A giant see-saw to weigh pupils against a pile of kilograms will take up too much time; but it might be a good 'progress activity' in the corner of the lab.)

c. Show a transparent plastic box 10 cm × 10 cm × 10 cm. Place it on a kitchen spring balance. Fill it with water and compare it with 1 kilogram. Or, better, use an equal-arm balance; place the box of water on one side and a kilogram on the other, accompanied by an empty box as a tare.

d. Show a metre cube of cardboard. Ask: 'how many 10 cm × 10 cm × 10 cm boxes would fit into that? Then how much water could it hold?

e. Some pupils may already know about density from other science teaching. For those who do not know and understand the concept, this is certainly *not* the time to discuss or define it—it will not be needed for some time yet, and introducing it now would make a discouraging start. But with any who do know it, a quick question, 'what is the density of water?' will start discussion. ('One?' 'Yes, 1 gram for each cubic centimetre: a gram; a thimbleful. But now our standard units are kilograms and cubic metres. What is the density of water in kilograms for each cubic metre?') Refer to the 10-cm cube of water—which should remain on show—to argue against offers of density of 1 or 10. This is no moment for drill; but a quick conjuring trick with some patter of questions could be a useful and interesting start.

S.I. UNITS

The Association for Science Education has published valuable guidance for the use of the international system of units (S.I.) and Examining Boards have accepted these recommendations to a large degree. However, it would be unwise to overlook the teaching problems which arise. These problems make it unlikely that pupils studying physics before O-Level can accept the full canon from the beginning of their course.

Because Nuffield Physics is a developing programme, we believe that the system of units used should develop to match the growth and interest of the pupils. In this way best help is given.

For example, the unit of velocity will take the form *metres per second* in the early stages.* This will lead to *metres/second as the programme develops and can finally appear as m/s* in accordance with the condensed form suggested for the O-Level candidate.

Acceleration presents a more difficult case. The term *metres per second per second* presents immediate difficulties of comprehension; and these may well be eased by reference to *kilometres per hour in each second*. When the necessity for the double time-units is clearly understood by the pupils, the form *metres/second per second* becomes appropriate; and this in turn can be shortened to *metres/second*^{2} and later to m/s^2.

In general, we hope teachers will join our view that there is nothing wrong in writing units out in full—except where one is publishing a compact report in a learned journal. We continue to use expanded forms to avoid some stumbling-blocks for pupils who are learning for understanding.

PROPORTIONALITY IN THE OUTCOME OF TROLLEY EXPERIMENTS

Here again we offer mathematical forms to those who like them. All pupils see the relationships of FORCE, ACCELERATION and MASS in their experiments. They should extract two general statements:

I. for a given mass (e.g. one trolley),
FORCE $\propto$ ACCELERATION
or ACCELERATION $\propto$ FORCE

II. for the same acceleration,
FORCE needed $\propto$ MASS

{For some pupils, these are clear concepts of proportionality, easily expressed in symbols and then combined in an overall rule. For others who do not have a strong mathematical interest, these will be at most vague qualitative ideas of how force and motion go together. So, for that section of the year's work in a band of pupils of mixed abilities, there should be a parting of the ways between those pupils who will use with confidence mathematical tools that will carry them to O-Level standard; and others, for whom drill in proportionality arguments would be dull or meaning-

* Even here, the use of the word 'per' needs some teaching and the abbreviation '/' makes the meaning no clearer to many. We habitually take the meaning for granted and leave the structure a stumbling-block for some beginners. We should change 'per' to 'for each' and give some examples: like this:
the PRICE OF ORANGES . . . 5p *for each orange*, 60p *a* dozen
And for SPEEDS: 40 kilometres *travelled in every hour*
Only when the meaning is made clear by examples of use, should we show how the value is arrived at by arithmetical division.

less and discouraging—intrinsically damaging to our aim that pupils should enjoy understanding physics.}

{We suggest that teachers should, thus, make different demands of different pupils. If that seems a denial of equal opportunity, we explain that we are trying to maintain *equal opportunity for each pupil to enjoy physics*, and thereby to profit within his or her own interests.

Reasoning from experiments to $F = ma$ Some pupils may like to see this reasoning; but most will gain a fairer picture of physics if they just accept the result and proceed to further experiments and some problem-solving. So this discussion is only offered as an *extension* of the normal teaching.

To see how $F = ma$ can be reached as a summary of trolley experiments, pupils need to express the following statements from their experiments:

FORCE $\propto$ ACCELERATION and
FORCE needed $\propto$ MASS

in symbols, then combine them in $F = K\,ma$, and then choose units to make $K = 1$.

Conversion to symbols is palatable for most pupils—'just shorthand'—thus:

$$\frac{F \propto a \quad \text{and} \quad F \propto m}{F = Ca \quad \text{or} \quad F = C^1 m}$$

But the combining of those two relationships is a stumbling-block for many. We might prepare for it with a story like this:

'Suppose you want to paint the wall of a room. How much will the paint cost? Common sense tells you that:

I. The cost will be proportional to the length of wall.

II. The cost will be proportional to the height of the wall.

You can say COST $\propto$ LENGTH
and COST $\propto$ HEIGHT

You can combine both those in one statement and say:

$\therefore$ COST $\propto$ LENGTH OF WALL $\times$ HEIGHT
$\therefore$ COST $= K \times$ LENGTH OF WALL $\times$ HEIGHT,
where K is a constant number.

In the same way, we combine the statements for force and motion and say $F = K\,ma$.

Few will be convinced; and with most pupils we should not labour the business of arriving at that; and we should not labour the further change to make $K = 1$.

We might answer a few keen enquirers by saying:

'Instead of having $F = K\,ma$ we want to have the simpler form $F = ma$, with K disappearing because it has the value of 1. We can get what we want by taking what we want and then paying for it. We write $F = ma$; and then we try to find what a force of value 1 must mean.'

Even for most pupils of medium ability and of high ability we should postpone most of that long discussion to A-Level and simply say that $F = ma$ sums up things the trolley experiments illustrated, and F is measured in newtons—universal unchanging units which pupils have been using for a long time now.

However, there is a difference: until now pupils have taken newtons as arbitrary units provided by the marks on spring balances—much as they have taken amps from ammeter markings. Now we can describe a newton properly.

CHAPTER 2

FORCE, MASS, ACCELERATION

Newton's Second Law; problems; Bernoulli paradoxes

AIMS AND PLANS—A DISCUSSION WITH TEACHERS

{Pupils of this age want to know where they are going in a programme of study. They ask, 'Where does this lead?'; or there may be a more unhappy question—coming from either pupils or teachers—'Why are we doing this?' Sometimes such questions come only from a general uneasiness over a new programme and call upon the teacher's feeling of confidence and enjoyment, rather than needing a specific answer.}

{But sometimes the questions are voicing a complaint over demands which make the work seem difficult and uncertain when compared with the method of learning science by memorising facts and rules. Those demands are important matters in our policy: we do ask for reasoning to be done; we do give problems to be thought out; we do pose questions to be kept partly answered for some further thinking—and all those are of the essence in our teaching.}

{We should meet complaints of difficulty and feelings of uncertainty very gently, because habit is there from other teaching and, particularly with slower pupils, our new demands do feel harder to meet.}

{We should reply both to such complaints and to questioning of our aims by giving examples of the physics we are dealing with, and by outlining, from time to time, the work that lies ahead. We should not reply by making fun of parrot-learning; but we should point out the advantages of doing one's own experiments and some of one's own thinking, so that one understands well and will keep that knowledge.}

{There is a possible moral here for pupils' work in later life. We are trying to praise the capable, well understood knowledge of a job that breeds enjoyment and success. We may be laying the foundation for a shop assistant's pride in knowing the stock, a waiter's pleasure in welcoming customers, a bus conductor's keen knowledge of geography, a surgeon's insistence on spiritual contact with his patient, and in general the satisfying self-respect of seeing a job through.}

We are now approaching Newton's Second Law of Motion through experimental illustrations. As research scientists often do in starting an investigation, pupils should first run through rough trials to survey the problem.

Preliminary Class Expt 15 Short preview: pulling trolleys

(OPTIONAL: a quick reminder or preparation for pupils who feel uncertain.) This is a rough trial for the sake of a feeling of how things behave, not for seeing other people do the experiment. Pupils pull the trolleys with elastic cords but they use no timer or other measuring instruments.

Apparatus

dynamics trolleys ‡	item 106/1
elastic cords for pulling trolleys ‡	106/2

Runways are not necessary here; smooth tables will suffice. Although pupils may have to do later trolley experiments in groups of four (owing to the size of runways and problems of storage), pupils should work in pairs now if possible.

‡As many trolleys as the lab has, up to 32, should be brought out, and there should be plenty of elastic cords.

Procedure

Pupils follow these instructions:

* * * * *

This is a preliminary experiment to see the kind of motion you will be measuring next. Just to remind yourself, try pulling a trolley ***without making measurements****. Watch the motion each time.*

(i) Pull a trolley along the table with a stretched elastic. Stretch the elastic until it is as long as the trolley and keep it stretched like that while you pull the trolley and run along beside it.

Then pull with two stretched elastics side by side; and then with three.

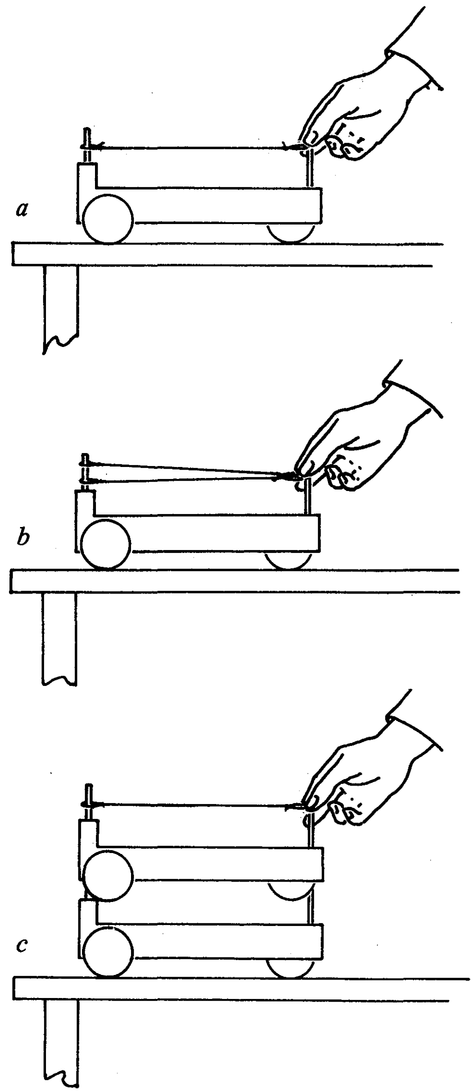
(ii) Then try a single elastic's pull on more stuff-to-be-pulled. Pile one trolley on another and try pulling that double mass with one stretched elastic.

* * * * *

All we expect from the first part of the experiment is qualitative knowledge that a bigger force makes an object accelerate faster.

For the second part we hope for the qualitative knowledge that with more stuff to be accelerated we expect a smaller acceleration.

Some of that may have been clear in Year 3 but pupils must see it clearly now because the class is to investigate with considerable care.



QUESTIONS ALREADY

Problems with unexpected difficulties: help or hindrance? Sometimes we suggest, intentionally, problems that involve knowledge that is yet to come in the programme, problems that must, therefore, be left unfinished for the present. These are offered as 'sales talk'.

We like to think of our work in teaching physics as far away from the hard-headed ways of the advertising man. And yet we can learn much from his skill in 'creating a demand', in putting a customer in the frame of mind to want what he is going to be offered. For example, the advertisement does not just say, '*Go and buy Sunflower soap; you must have it.*' It asks more delicately, '*Can Sunflower soap really make you more beautiful?*'

We have put some problems at this point in the Pupils' Text, labelled 'Questions which look ahead'—with an admission that they do need later knowledge.

One of those asks about a family of children pushing a car that has run out of petrol—sales talk for Newton's Laws.

Another asks readers to think about forces in a crash, such as a watch falling to the floor, or a baby rolling off a sofa.

Another raises a question about a rocket that has ascended and turned into orbit. (This can lead to two accounts of a rocket's propelling force; and it deserves a demonstration of the water rocket—see the box.)

Demonstration 16 Rockets

Show a rocket now or later—explanations come in Chapter 5.

Apparatus

Either	1 water rocket ‡	item 167
or	1 CO_2 capsule rocket ‡‡	168
Spare CO_2 capsules		168/1

‡ Various water rockets are obtainable from toy shops. (A suitable one is made by Merit: Lunar Rocket, cat. no. 9220.)

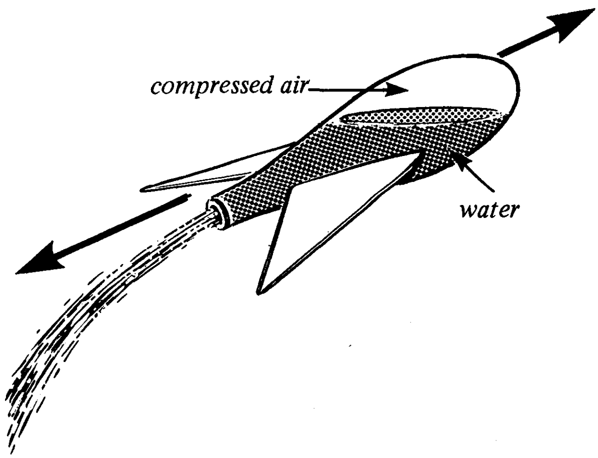
‡‡ CO_2 capsule rockets are obtainable from toyshops. One manufacturer makes a simple truck to take a CO_2 capsule.

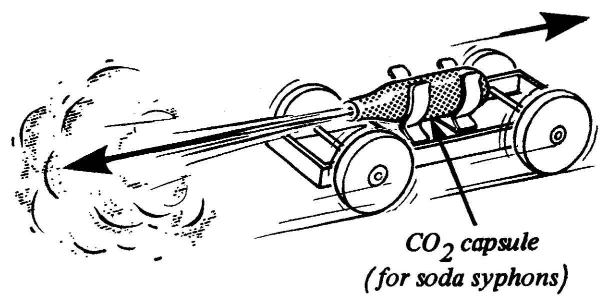
A simpler arrangement: attach a CO_2 capsule (as used for soda siphons) to the top of a toy truck. The capsule should be horizontal with its neck facing the rear of the truck. Use Sellotape for fixing, or attach an aluminium tube and then fix the capsule inside it.

Procedure

a Fire a water rocket

or b break the capsule of a CO_2 rocket with a round nail given a sharp blow from a hammer. The truck will move at high speed across the table or floor.





There is a problem on testing the brakes of a racing car which would have to be left unfinished now—the calculations postponed till pupils can use $F = ma$ with absolute units for force.

Teachers may possibly want to direct pupils to some of those early problems, to promote interest, to lead to the new experiments and ideas—perhaps to help by creating a demand.

PUPILS' EXPERIMENTING ON FORCE, MASS AND ACCELERATION

{Our experiments on F, m and a are not easily done with great precision unless pupils have time to practise techniques and make careful measurements and have a flat board for the trolley to run on.}

{By giving pupils full clear instructions and helping them whenever they are uncertain, we could reduce the time taken for these experiments enormously; but, if we do, we have missed the point of the experiments.}

{These are intended to be investigations made by pupils *on their own*. We hope for the full satisfaction that young people can get when their own measurements reveal natural behaviour clearly.}

{If some pupils experiment too roughly and do not arrive at convincing results, we should neither blame them nor hurry them on to other things. We might offer them a chance to try again: 'Are you satisfied with this? Knowing what you now know, how long would it take you to try this over again very carefully?'}

{Even as early as Year 4, self-respect is sometimes waiting to push its owner towards a careful second trial, if only we will give suggestions and approval. Time taken for such further trials will be justified—there are other things this year which could be cut short.}

{On the other hand, this investigation should not drag on into a long and tedious business of repeated measurements by pupils who do not clearly understand what they are driving at. This is not one of those experiments which turns out to be so fruitful that teachers decide to expand it next time they teach it. They are more likely to carry it through a little faster with next year's class, by some coaxing and some more careful preparation.}

{These experiments can give some pupils a satisfying sense of being knowledgeable, a feeling that they have got the better of the apparatus—that they are apprentices who have grown expert with it—and that they are finding out things about nature by making good measurements. Although these investigations will take several periods, they are the pupil's own experimental work and they are worth the time.}

Careful measurements Now ask for really careful measurements. If possible, discuss plans towards the end of some class period, so that pupils have time to think about the experiments ahead of them next time.

NEWTON'S SECOND LAW: FORCE AND ACCELERATION

Force and acceleration with vibrator and tape Pupils pull a trolley and use timer and tape to record its motion along a friction-compensated plank. To make that compensation they tilt the plank to a slope such that a trolley will just keep moving steadily downhill once it is given a start. With good wheels on the trolley and a smooth, flat plank, this slope is small, so friction compensation may seem unnecessary. But it is probably wise to ask pupils to arrange this, as a matter of principle. In later experiments on momentum conservation even small effects of friction will damage the story seriously.

For a standard pulling force, pupils pull with a rubber thread stretched to an agreed length.* Each cuts his tape into strips 10 ticks of the timer long—10 spaces from dot to dot. Then he pastes those 'tentick' strips of tape in his notebook to make a 'tape-chart'. (But soon pupils will also draw a new form of graph.)

Pupils repeat the experiment with double pull, two elastics in parallel; then with treble pull.

* In all these experiments the force is applied by rubber cords (or spring balances) in parallel; and measured by counting the number of them. Although this requires practice and does not lead to very accurate methods, we urge teachers to avoid using THE WEIGHT of a pulling load instead. Although that is simple and accurate it leads too easily to confusing trouble over mass, weight and g.

Class Expt 17a Force and acceleration: Newton's Second Law

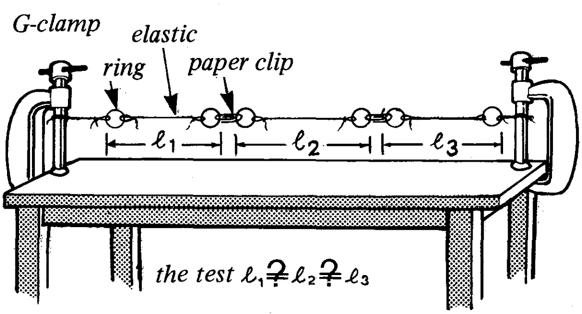
Apparatus

8 to 12 dynamics trolleys	item 106/1
40 elastic cords for accelerating trolleys	106/2
8 to 12 ticker-tape vibrators	108/1
8 to 12 runways	107
8 transformers	27
wood block or books	

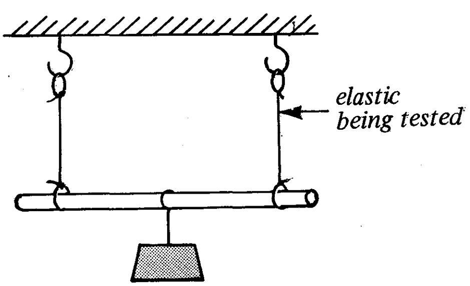
Preparation

Trolleys Check the wheels of each trolley. The outcome of the experiment depends on their good behaviour.

Elastic cords It is essential to give each group of pupils three *matched* rubber cords—inequalities will make the outcome obscure. Carry out some form of testing shortly before the experiment. Suggested methods:
(i) Hang up the cords and apply a standard load to each in turn. Collect batches of cords with similar stretch constants.
(ii) Make a horizontal 'daisy chain' of several elastics, joining them with paper-clips. Lay the chain on the table, stretch it, and measure the lengths of elastics *while they are stretched.*



(iii) Test pairs of elastics by hanging a bar on them, loaded at its mid-point. If the two elastics are unequal the lower bar will not be horizontal.



Procedure

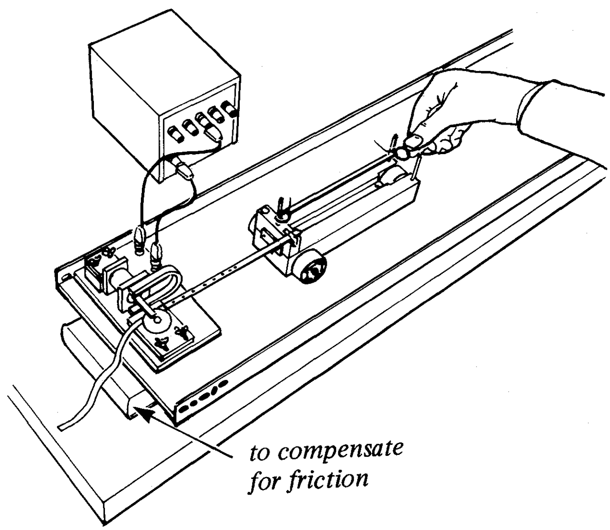
Before making measurements pupils need to compensate their runway for friction. Discuss the need with them and explain the method of compensation. They find the tilt needed to keep the trolley just moving down the slope at constant speed (once given a start). They must do that *with the trolley dragging tape* because the tape and timer add some friction. They make sure that once the trolley is started the distance from one dot to the next is nearly constant for a considerable run. (Watching the trolley's wheels gives a rough first test.)

Many pupils tilt the board far too much, in a hurry to get on with the experiment. We advise teachers to check the adjustment by watching a trial run.

Pupils follow these instructions:

* * * * *

This is going to be a long, careful experiment in which you pull a trolley with a steady pull and find out about its acceleration for different amounts of pull.



Friction compensation Before you start pulling the trolley you must make sure that friction will not spoil your experiment. Compensate for friction by raising the starting end of your runway a little so that the runway slopes gently downhill. Put one thin book (or piece of wood) under the starting end. Give your trolley a start and let it run down the hill, pulling some tape (because that adds friction). If it moves faster and faster you have tilted the runway too much. If it moves slower and slower you have not tilted the runway enough.

To see whether you have succeeded in arranging that friction compensation, look at the tape and see whether the dots are spaced apart at equal distances.

The pull Now attach about $1\frac{1}{2}$ metres of tape to the back of your trolley so that you can record its motion. Pull your trolley with one elastic stretched to standard length. You may find this easiest if you put the ring at one end of the elastic on the post at the back of the trolley, and pull the other end until the ring is just level with the front of the trolley. (If you like, put a pencil through the front ring and pull with the pencil, holding it vertical.)

Walk with the trolley, keeping the force steady.

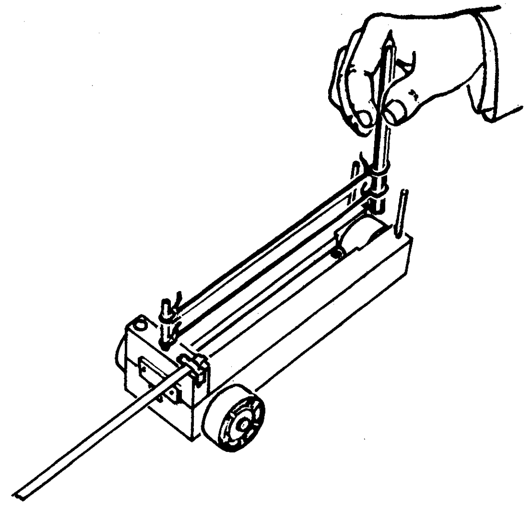
If you work with partners, each partner should make his own tape record.

Choose a clear dot near the beginning of your tape, mark it 0. Count along the tape to dot no. 10. Mark that, and mark dots 20, 30 . . . . Cut your tape at the marked dots so that you have a set of tentick strips.

Tape-chart Paste your set of strips side by side on a sheet of paper, with their feet all on a horizontal line.

Look at the heads of your strips. Do they make an even 'staircase' of strips? What can you say about the motion of your trolley?

Double pull Then start again, pulling the same trolley with two elastics side by side to make double force. Make a tape-chart of strips from this.



Triple pull Then start again and pull with three elastics side by side. Again make a tape-chart.

*   *   *   *   *

TAPE-CHARTS AND GRAPHS

Tape-charts once more We want to make sure that pupils understand the idea of samples of velocity. Tape strips are more basic than graph points. They are material extracts of distance-travelled; while graphs are more artificial representations. Graphs are soon to be our standard scheme; but pupils should make tape-charts for the previous experiment. The tape-chart also suggests the concept 'distance is given by area under a velocity-time graph'; and it provides for some valid examination questions.

To many a professional physicist this distinction between a tape-chart and a graph appears trivial; and there is a strong temptation to omit the chart and proceed straight to adult graphs. But to young pupils who cannot know clearly in advance where their studies are leading tape-charts offer valuable teaching—which we shall use in our formula-making soon.

Some teachers have reported pupils more than ready for graphs and have omitted trying a further tape-chart. Since we are not sure whether such reports arise from pupils' impatience or the teacher's own skilful habit, we make this plea for one more chart now.

If pupils do plot a graph instead of any tape-chart, they should, at this stage, plot it with many points—equivalent to many strips of tape—so that they can see whether the acceleration is constant.

Graphs Then pupils should draw graphs from the same tapes. Each graph can have just two plotted points provided the chart has already shown that the acceleration is constant.

Pupils take a speed represented by a length of tape, which is distance travelled in ten ticks and then another tentick length a known time later, say 50 ticks later. They plot these two speeds (upwards) measured in cm/tentick against the time (along), measured in tenticks. Then they draw a straight line through their two plotted points. Although this misses the advantage of averaging, it makes a simple graph that is easier to look at.

(If the runway is not very flat and smooth, local variations of motion will make this use of two points quite unreliable. Therefore, it is essential to use a runway such as a plank of blockboard held flat by angle girders along each edge. Otherwise, many points must be plotted and some kind of average arrived at for the motion.)

Acceleration in metric units Point out that the chart for accelerated motion is really a graph, with SPEED plotted upwards and time plotted along. Pupils have plotted SPEED in odd units, centimetres travelled in 10 ticks (centimetres per tentick), and time in very odd units, one tape-width representing a tentick from the half-time of one strip to the half-time of the next.

Pupils' Text 4 carries pupils through the move from tape-strips and odd units to the expression of accelerations in standard metric units. There is a detailed discussion of examples. And then that continues to the use of the AREA under a graph of SPEED versus TIME in deriving formulae.

Class Expt 17b Graphs to show the story of the tapes

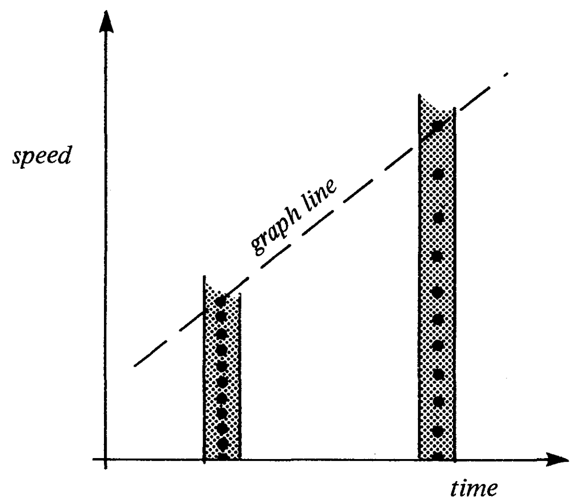
Apparatus

centimetre rulers	item 502
graph paper	238

Procedure

Each pupil plots his three graphs for these experiments *on the same sheet of paper*.

Encourage pupils to draw conclusions from their graphs. It is much less valuable, though much quicker, for the teacher to impose a well-taught conclusion. What pupils find out for themselves from the slopes of these graphs (without even being told to look at the slopes) will remain in their minds as one of their discoveries in physics, particularly if we can then tell them that they are finding out part of Newton's great Laws of Motion.



Useful questions to be asked in teaching When plotting a graph of SPEED versus TIME for a car speeding up with constant acceleration, ask two questions:

1. *(To start some thinking about mass)* 'What graphs would you expect for the same car loaded up with a great many passengers and pulled *with the same force*?'
2. *(To keep in touch with the real world)* 'Do you think that this graph would go on up for ever with a real car, continuing its straight line?'

That last question may lead to the common-sense answer that air resistance will change the story. Make it clear that the different motion that we then expect is not 'wrong' but is just what does happen in nature.

Useful broadening And to avoid pupils' building an idea that the *only* right kind of accelerated motion—or the only common kind—is one in which the acceleration is constant, show some example where the acceleration changes obviously. (The descending chain described earlier does well—Experiment 8. And just think of S.H.M.)

DEALING WITH MASS

{**Mass** When we change the MASS of the moving object in experiments on force and motion, pupils are apt to find the interpretation more difficult, for two reasons:
(i) Because to them MASS is more artificial, less familiar, than FORCE—contrary to the view of physicists and philosophers who prefer to make mass fundamental and force secondary.
(ii) Because they have no great interest in the part played by MASS in accelerated motion, they feel no compelling reason to investigate it.
(iii) The *reciprocal* relationship between F and m for constant a is itself a barrier.

So we should make our test appear as easy and clear as we can.}

{For professional physicists, or for very able pupils heading for O-level and A-level and more physics, a clear test would be to apply the *same* force F to masses M, $2M$, $3M$, and look for accelerations in proportions $1:\frac{1}{2}:\frac{1}{3}$. Teachers might suggest such a test in an *optional* experiment.}

{For a general group of pupils there is little point in driving everyone to the reciprocal relationship, either by argument beforehand or by extraction from the experiment—either way will seem dull and incomprehensible to many.}

DIFFERENT MASSES

Yet O-level pupils should make some test of this aspect of Newton's Second Law; so we suggest a modified approach: try different masses, but *aim for the same acceleration each time*. The trick is to apply forces F, $2F$, $3F$ to masses M, $2M$, $3M$ respectively and see whether the acceleration is the same each time. Therefore ask pupils to guess what force is needed to give double mass the *same acceleration* and then test their guess.*

{This is not the formal move of 'framing an hypothesis' advertised by some theoretical philosophers of science. It is something easier and very useful in science, *acting on a hunch*, hoping for a simple answer. We can tell pupils that such guessing is good science, so long as we test it and abide by the test.}

That guessing approach is described in *Pupils' Text 4—without giving the answer*. Able pupils heading for O-Level, should find that guidance sufficient and we hope they will enjoy discovering a good guess.

(A day or two before pupils try this experiment ask them to think about this question:

Suppose you have a force that gives a trolley a certain acceleration. Imagine you put another trolley on top of your trolley and pull them both. Can you guess what force you would have to use if you wanted to get the *same* acceleration as with one trolley?)

Others may find that insufficient. Either let them omit the experiment or lead them quickly to a definite answer to be tested, by something like this:

Think of pulling a pair of trolleys side by side. Each needs a rubber cord to pull it. Two rubber cords side by side would get them both going equally. Try that, but add the second trolley by piling it on top of the first one.

Pull one trolley with one stretched cord; two trolleys with two stretched cords; then a pile of three trolleys with three stretched cords.

That would get the experiment done; but what picture of science would that give those pupils? We would rather urge teachers to omit the experiment for pupils who are not ready to face the question for themselves.

Class Expt 17c Accelerating more passengers: the cunning test *F versus M*

In this experiment we suggest a special choice of forces and masses, from which we expect to obtain the same acceleration in each case. Therefore, detailed measurements are not necessary: *any* timings which show that the acceleration is (approximately) the same in all three cases will suffice. A measurement of the *total* time of the motion from rest to some chosen end-point will do. (This could be done with a stopwatch if the total time were not so short.)

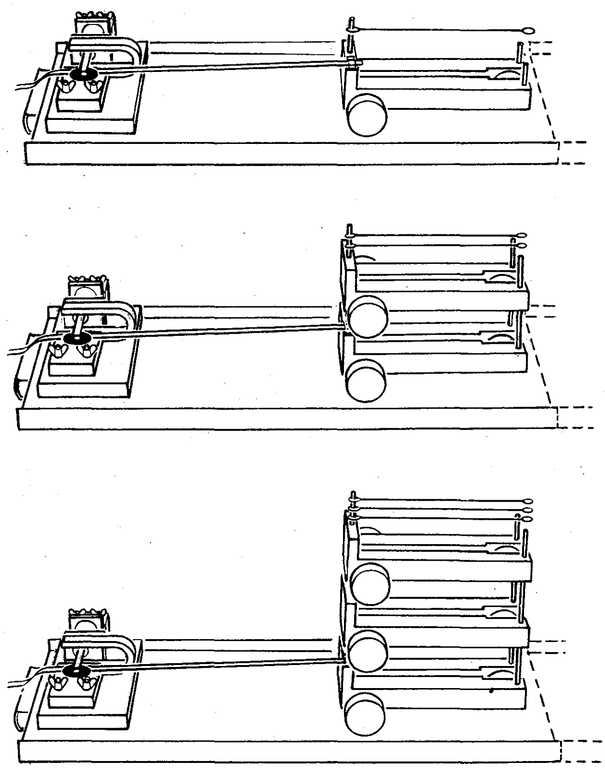
This is a proper part of our O-level programme; but teachers may decide to omit it for some members of the class. Therefore we list below the apparatus needed for *each pair of pupils*—or, if many try it, *for each quartet*. For those who do try it, the value of this experiment

* Although the scheme we suggest here looks like trickery—a prearrangement to produce a simple answer—it is in fact a clear illustration of the basic story, that *masses do not interact*, and that *forces do not interact*; so that when we have two masses side by side each needs its own share of force to accelerate it. One mass does not affect the other one's force-requirement; and one force does not affect the ability of a neighbouring force to accelerate things.

rests in personal experience so it should remain a class experiment for them. (Others, who miss it now might see it as a 'pupils' demonstration' in Year 5.)

Apparatus for each pair or quartet

3 dynamics trolleys	item 106/1
3 elastic cords (and spares)	106/2
1 runway	107
1 ticker-tape timer	108/1
1 transformer	27



Preparation

Trolleys. In this test, good behaviour of the wheels is important. Pupils will drag one trolley along the runway, first alone, then loaded with another trolley on top, then with two trolleys on top. The second and third trolleys simply act as additional masses, so their wheels need not run well; but it is important to check the wheels of each group's first trolley beforehand.

Friction compensation. This is important here. Fast pupils should certainly make their own friction compensation, though the teacher should watch a test. But some pupils may find the experiment difficult enough without all the trouble of making and testing friction compensation. And for them, it might be advisable to provide friction-compensated runways, and one tested trolley.

Elastic cords. It is essential to give pupils a supply of *matched* rubber cords—inequalities will make an already difficult discovery impossible. Carry out some form of testing shortly before the experiment. Suggestions are given in Experiment 17a.

Procedure

Pupils follow these instructions:

* * * * *

Preparation

Set up the runway and compensate it for friction. Test your compensation carefully.

Set up the timer at the higher end. Arrange a trolley to pull tape through it. That trolley must have good wheels. It should be the trolley that you used in arranging friction compensation.

Thinking and planning

In this experiment you will see what happens when you pull more MASS. Try doubling the mass. That means having twice as much stuff to accelerate. You can arrange this by piling one trolley on top of another. Then you will be pulling two trolleys, twice as much stuff.

After that you can arrange three times the mass, by piling one more trolley on top. (If necessary borrow the third one for that.)

It may be difficult to see the relationship between acceleration and the mass you pull. You might pull with one stretched cord each time: first on one trolley, then on two trolleys, then on three trolleys. But you would have to calculate very carefully from your measurements to see the connection between acceleration and mass.

A clear quick test

Here is an easier method instead. *Try imagining the answer first*; then make a simple test of it. (This is very good science. If you have a hunch, or can make a guess, use that to predict what will happen in an experiment. Then try that experiment as a test.)

Guessing with a hunch

Instead of using the *same force* each time, try to get the *same acceleration*. Ask yourself:
'How much should I pull on *two* trolleys to get the *same acceleration* as when I pull one trolley with *one* stretched cord? And how much should I pull on *three* trolleys to get the *same acceleration*?'

Guess the answers and try them.

(If you want double pull you can pull with two equal rubber cords side by side.)

The experimental test of your thinking

(i) Pull the trolley by a single rubber cord and obtain a trace. Start the trolley from rest, and start the tape when the trolley starts. (To do this, set the timer going, but hold the blade with a finger. Release the timer's blade at the same instant as the trolley.)

If you are sharing with partners, *each partner should make his own tape.*

Keep your tape carefully.

(ii) Then stack another trolley on top of your first trolley to make a double mass, twice as much matter to move.

Check the friction compensation. (You now have twice as big a load on the wheels and the slope for friction compensation may be the same or it may be different. Therefore you must check it and if necessary change the slope of your runway.)

Pull the double mass with whatever force you *guess* will give it the *same acceleration.*

Look at your new tape. Does it confirm your prediction?

If you have the same acceleration, the new tape must look just like the old one. On each tape, count five (or ten or twenty) tenticks from the start. Then compare the total distances.

(iii) Continue your test, pulling three trolleys with the force that you *hope** will give the *same acceleration.* Make the test.

What does this experiment tell you? Discuss it with your teacher.

* * * * *

Note: For clear, convincing results, it is important to adjust the friction compensation again for each new mass. We might expect the proper tilt to be the same for several trolleys as for one; but in practice it sometimes changes and unless the compensation is checked, measurements may be puzzling.

*Yes, *hope*. It is quite respectable in science to *hope* you will find a simple story. Then it is good if you find your guess is true. But it is bad if you find your guess does not fit and yet go on sticking to it because you hoped!

DISCUSSION OF FORCE, MASS, AND ACCELERATION

When pupils have finished their experimental investigations and have some form of graphs in their notebooks to show the results, hold a general discussion. Encourage pupils to offer suggestions and argue with each other.

It would be a pity to issue a clear summary at this point; but by now pupils should have seen for themselves that:

1) A constant force makes the trolley accelerate, with constant acceleration;

2) Doubling the force doubles the acceleration and so on. Thus the accelerations 'produced' are directly proportional* to the forces.

3a) The force needed for a chosen acceleration is proportional to the mass. The mass is measured by the number of equal items piled on top of each other. We can carry that down to the atomic scale and say that mass is a measure of the number of atoms in a body, provided they are all of one kind.

{And if we like to lump protons and neutrons together under the name 'nucleons' and regard them as the fundamental constituents of atomic nuclei, we might even say that mass is to a rough approximation a measure of the total number of nucleons in a body, whatever the mixture of atoms in it.}

3b) When a chosen force acts upon different masses the accelerations are inversely proportional to the masses. We should expect a much more naive wording of this from pupils; and we should be unwise to give 'inverse proportion' as our statement.

* We should remember the confused views on 'proportionality' that cloud the minds of many pupils at this age—goodness knows why. (See the note on 'proportionality', in the General Introduction with *Teachers' Guide 3.*) Whenever we meet proportionality we should try to avoid that long word at first and say simpler things like this:

'When you double the force, you get double the acceleration, when you use three times the force you get three times the acceleration, and it goes on like that. Acceleration 'goes as' the force. They both go up in the same proportion. We say that the acceleration is *proportional to* the force.'

Here we are measuring force by the number of equal pulls in parallel, assuming that such forces simply add, and do not interact—to an enquiring pupil, we might say, 'They do not frighten each other; nor do they encourage each other.' (See the note on 'interaction' in the General Introduction issued with *Teachers' Guide 3.*)

$F = ma$ AND ABSOLUTE UNITS

Pupils' Text 4 describes two general moves that follow the experiments:

(i) We combine the two relationships:

$F \propto a$ for constant m

$F \propto m$ for constant a

in a single statement of proportionality:

$F \propto ma$, or $F = Kma$

(ii) We compel K to take the simple value 1.

The combining of two proportionality statements into one overall proportionality is often difficult and puzzling for beginners. We should not insist on getting this thoroughly learned and understood at the O-Level stage. We should be content to make a jump to the final form.

Then we may show those pupils who are interested that it contains the two experimental forms—thus we justify the final form by working backwards. For most pupils the result of both changes, $F = Kma$, should suffice without explanation.

We compel K to take the value 1 to suit our liking for arithmetical simplicity. And we pay for our selfish simplification by a choice of unit for force, the newton.

Force units We tell pupils we are going to invent a new unit for force, to save trouble and later confusion. We have a kilogram for unit mass, one metre/second per second for unit acceleration; and for our own convenience we choose the size of the force unit so that K will be 1. This is rather like the attempt that was made long ago to choose the size of one gram so that it would make the density of water 1 in centimetre-gram-second units. That may be a clever device for ease in calculations, but it is not always a clever device for teaching, because the constant, having the value 1, becomes concealed.

{Physicists are quite used to having K equal to 1 in $F = Kma$ and having the density of water 1 in the older metric units; yet most of us are slightly shocked when we find Relativity experts taking the speed of light equal to 1 in order to 'simplify things'. The effect of that latter change is to make m and mc^2 indistinguishable; and, for a light-quantum, the momentum also has the same value as m or mc^2. Those of us who have a qualitative feeling that mass, momentum and energy are essentially different concepts, are offended by this high-handed treatment—although the experts may persuade us to swallow some of our annoyance.}

{Pupils may think it strange to invent a new unit of force now, when we have taken force as the obvious well-understood thing all along. Force has been, in our treatment, a push or a pull measured by counting the number of stretched rubber strings in parallel. And mass is still emerging as a new concept. It might have seemed more suitable if we had chosen to name a new unit of mass and taken some familiar unit of force. However, there are two objections to that: (1) the decisions were made long ago and are now too widely accepted for a change to be feasible; and (2) we do not have a *reliable* old fashioned unit of force.}

{Neither the kilogram-weight nor the pound-weight is reliable, because the actual size of such a unit of FORCE varies over the surface of the Earth and would be quite different if we ventured to the Moon.}

{The reversal of choice of units—a strange new unit for the old familiar concept FORCE, an old unit for the new concept MASS—need not worry us. To pupils, the units that we choose for measurement are just the things in which the scales are marked. They find an ammeter graduated in amps and learn to use them for measurements of current. And they even develop a sense of size—one amp is a small current and 100 amps a very big one. It is only much later that they learn about an absolute definition of an amp in terms of two wires 1 metre apart.}

{From time to time, however, there has been talk of a 'universal kilogram force' such as a 'standard kilogram-weight-at-London' to be transferred by use of some spring balance to all other places in the world. That is a perfectly feasible constant unit favoured by some scientists, but it is likely to look rather foolish when we go to the Moon. In modern physics teaching pupils use newtons for forces from the beginning; they will meet newtons in other sciences—and, just as important, they will meet joules, watts and volts which derive from the newton.}

{Some pupils will meet pounds and kilograms used as units for forces (meaning pound-weight and kilogram-weight) in ordinary life, and pounds per square inch on tyre gauges; but we do not think it advisable to preserve those units in teaching.}

{There is nothing wrong with alternative unit schemes; but there is nothing world-shaking about them either—a change of units will not alter the facts of nature. We hope that teachers who are busy helping pupils to understand our knowledge of nature will be able to avoid long arguments with those enthusiasts who believe that a change of units will make a profound change in physics. Here we simply offer a decision and then hope to get on with the real physics.}

THE UNIVERSAL ABSOLUTE UNIT OF FORCE: ONE NEWTON

With most pupils, we should not labour the business of making $K = 1$. We should simply say that we are going to use force units which are called newtons, units which are the same size of force everywhere. And, with newtons, the relation is $F = ma$.

If pupils want some justification, we can say: To find out what one newton of force is like, take $m = 1$ kilogram of mass; take $a = 1$ metre/second per second for the acceleration; and ask what force will produce that. The force must be:

[1 kilogram] × [1 metre/second per second], and 1 × 1 is 1.

That means: a force 1 is the force that will give 1 kilogram of matter an acceleration of 1 metre/second per second. We could call that unit a kilogram · metre/second per second and that would be a good descriptive name; but it seems too long, and so we have chosen a single word to mean that. We honour Sir Isaac Newton, whose laws we are dealing with, and call that unit 1 newton.

Then 1 newton gives 1 kilogram an acceleration of 1 metre/second per second. As a unit, 1 *newton* is just another name for 1 *kilogram · metre/second per second*—just 'dictionary work'.

Class Expt 18 Feeling a newton of force

Apparatus

16 slotted 'weights', 100 grams	32/2

Procedure

Each pupil holds 100 grams, and feels the pull of the earth on it—1 newton.

Trying a pull of one newton Provide a 'forces box' for pupils to try pulling with a force of 1 newton. At a later stage the same box with an extended label will provide experience of an energy-transfer of 1 joule.

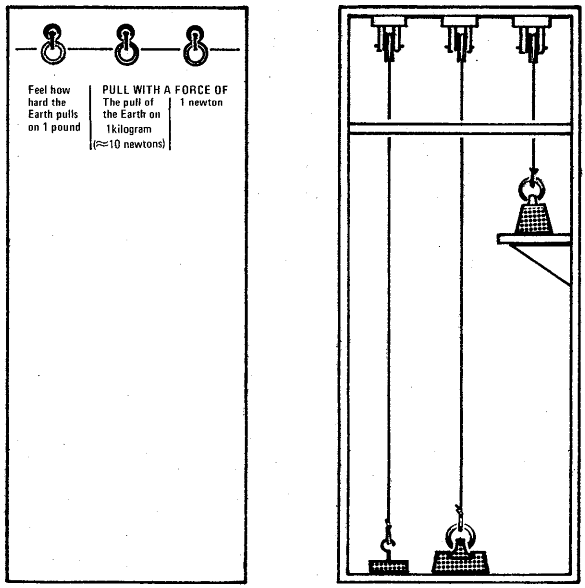
Pupils' Demonstration 19 Forces box

Apparatus

1 forces demonstration box ‡	item 63

‡ The label now runs (in revised form):
PULL WITH A FORCE OF
(a) 1 NEWTON
(b) THE PULL OF THE EARTH ON 1 KILOGRAM ($\approx$10 NEWTONS)
(c) FEEL HOW HARD THE EARTH PULLS ON 1 POUND

Some teachers may like to retain the 1-pound load of the earlier model, giving it the new label. Others may prefer to remove it completely.



Procedure

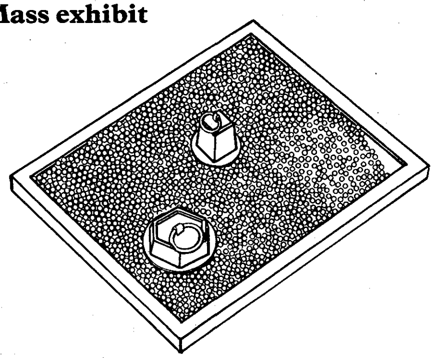
Pupils may have seen the forces demonstration box in an earlier year, but it should be available in the laboratory throughout the present stage as well, to give pupils a strong personal feeling for a force of 1 newton.

Mass exhibit The lab should have a mass exhibit on a friction-free table. Pupils push a standard mass with a finger and feel and see the results.

Pupils' Demonstration 20 Mass exhibit

Apparatus

1 mounted glass plate (30 cm × 30 cm or larger)	item 86
1 kilogram	32
1 wooden disk	
2000 small ball-bearing balls	231



Procedure

Set up the mounted glass plate and level it. Cover it partially with a layer of small steel balls (diam about 3 mm, or possibly $1\frac{1}{2}$ mm). Place a kilogram, clearly labelled, on a hardboard disk resting on the balls on the tray.

Pupils can push this standard mass with a finger to feel its 'inertia'. Keep the exhibit at the side of the lab for a few weeks if possible so that pupils can try this demonstration individually.

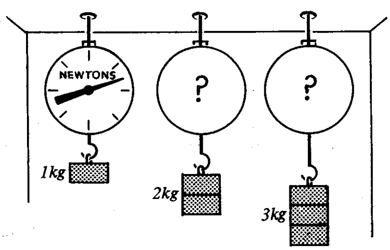
Note: Very small polystyrene beads could be used instead of ball-bearing balls; but they are more messy, subject to damage, and in general less satisfactory. If bought from manufacturers, steel balls cost less than £1 per 1000. For a glass plate 30 cm square, 2000 will suffice.*

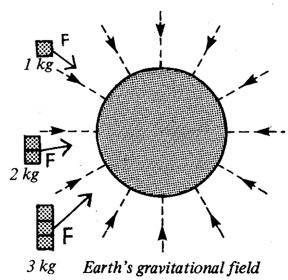
* Teachers who find that these small steel balls get carried away too freely as souvenirs might like to try the following experiment: appeal to pupils not to take them as souvenirs but at the same time give every pupil one or two balls to take home and keep. (Larger losses are claimable from the J. Willmer Home Experiments Endowment.)

FIELD STRENGTH g

Why is weight mg? Also discuss WEIGHT. We say the weight of an object is mg. If the object is a load hung on a string we say the tension in the string is mg. But if the load is held at rest it has no real acceleration g. (If we let go, the object does fall with acceleration g, but then the string has no tension!) So a sensible pupil will think it stupid to write mg for the weight of the load or the tension of the string, with g an acceleration which the load does not have at the moment. We can avoid that mystery, and save pupils from mistakes over units in problems, by giving g an alternative meaning.

Field strength As well as being an *acceleration of free fall*, g is the Earth's *gravitational field strength.* A spring balance (marked in newtons) shows that the Earth pulls 9.8 newtons on 1 kg; twice as much, 19.6 newtons, on 2 kg; and so on. The Earth's field pulls 9.8 newtons *on every kilogram.* We call that the Earth's gravitational field strength, 9.8 newtons per kilogram.





There is no actual force at a place near the Earth until we put some mass there. Then the Earth pulls like a giant invisible spring. The field itself is always there, a state-of-affairs-waiting-to-pull on matter.

If pupils are taught to use FIELD STRENGTH whenever they need to know the WEIGHT in newtons of m kilograms, they have much less trouble. They say, 'We know the Earth's field pulls 9.8 newtons on each kilogram; so the pull on m kg is $9.8m$ newtons.'

Thus g is generally more useful as a field strength than as an acceleration.

Show pupils that although the idea and use of field strength are different from those of acceleration, the units are equivalent. From $F = ma$, $\frac{\text{newtons}}{\text{kg}}$ are $\frac{\text{kg} \cdot \text{metres/sec}^2}{\text{kg}}$ or $\frac{\text{metres}}{\text{sec}^2}$.

Class Expt 21 Weight and field strength

Apparatus

16 1-kilogram masses	item 32
8 newton spring balances (10N)	81

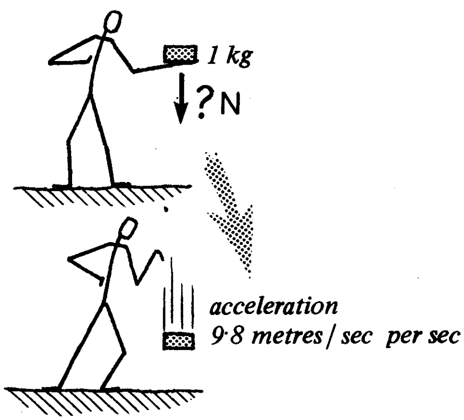
Procedure

Pupils follow these instructions.

* * * * *

(i) Hold one kilogram in one hand. Feel the force on your hand. *What causes that force?*

(ii) Then let the kilogram fall. You need not measure the acceleration, because you already know it. The kilogram falls with acceleration 9.8 metres/second per second.



Use $F = ma$ to calculate the FORCE that makes the falling kilogram accelerate. That is its WEIGHT, the pull of the Earth on it.

How big was the force you felt on your hand? How many newtons?

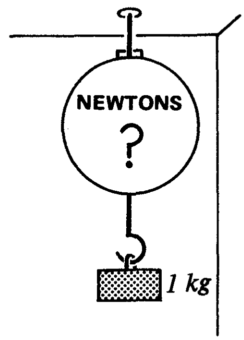
(iii) Now look at the force in a different way. Let it show you the Earth's gravitational field strength. Copy and complete the following in your record:

Pull on 1 kg (mass) is . . ? . . newtons

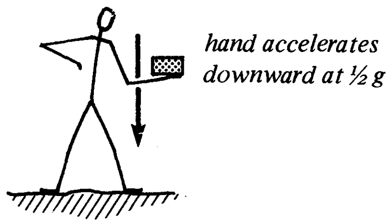
$$\therefore \text{ Earth's field strength } = \frac{\text{. . ? . . newtons}}{\text{1 kg}}$$

If I use 5 kg the pull is . . ? . . newtons

$$\therefore \text{ Earth's field strength } = \frac{\text{. . ? . . newtons}}{\text{5 kg}}$$
$$= \text{. . ? . . newtons/kg}$$



(iv) Now test a spring balance. Hang the kilogram on a spring balance that is marked in newtons. How big is the pull of the Earth on the kilogram, according to the balance? Is the balance correctly marked?



A puzzle Hold one kilogram in your hand. Try to move your hand downwards with an *acceleration* about $\frac{1}{2}g$. What force would you expect to feel pressing down on your hand? Do you feel a force like that?

* * * * *

USING $F = ma$

We shall not make a great many uses of Newton's Laws of Motion at once. We certainly should not put pupils on a diet of artificial problems such as Atwood's-machine calculations. However, we should give them some examples of calculating accelerations from forces and forces from accelerations. Problems relating to car driving, swimming races, and rockets, are probably fairly real to pupils. Homework and tests should offer such problems—a few at a time—to build confidence without delaying the progress of teaching.

Although problems on the motion of atoms and electrons involve very large or very small numbers—and compel us to provide data without explaining their origin as yet—we shall do a lot of good if we prepare for future work with atoms by using them as the moving things in problems. If pupils complain of the difficulty of handling the numbers in these problems we suggest practice with standard form. Perhaps pocket calculators can help—there are some calculators that insist on giving their answers in standard form; we should welcome these, especially for future A-Level physicists.

At this point, *Pupils' Text 4* gives half a dozen specimen problems with comments and, in some of them, answers too.*

In discussing dynamics questions with pupils, teachers will need to insist again and again on the contrast between MASS and WEIGHT.
MASS NEVER CHANGES. We measure it in kilograms; and a kilogram of chocolate is the same here and on the Moon, or even out in space.

For clarifying contrast, bring out the 'mass exhibit' again.

WEIGHT IS A FORCE, THE PULL OF THE EARTH (OR THE MOON ETC.) ON AN OBJECT. Weight can stretch a spring or make a trolley accelerate just like any other force. Its only peculiarities are: it is *vertical* and *unavoidable*. Use the field-strength 9.8 (or 10) newtons/kg to calculate a weight.

Weight does change when we move to a different place; from equator to North Pole (a small change); from Earth to Moon (from 1 down to $\frac{1}{6}$); from Earth to distant space (all gone).

As long as there is any doubt, continue to say 'pull of the Earth' instead of 'weight' (and avoid the misleading verb 'weigh', if possible).

When we supply data for a problem we may be able to leave it open for the pupil to make the right choice. In stating data, it is difficult to specify masses without involving the confusing word 'weigh', which will worry beginners, or at the other extreme giving the show away by saying at greater length, 'The mass is . . . .' We can avoid those difficulties, and leave pupils to make their own choice, if we word the data like this: 'A 5-kilogram cart . . . .' 'The 20-kilogram trolley is pulled by a 4-kilogram load hung on a string . . . .' That device is used in our suggested problems.

We also leave the pupil to choose when we ask 'how much does the Earth pull 2 kilograms?'

Those tricks in framing questions, though good discipline for the careful examination candidate, may be dangerous for pupils who feel insecure. The latter need different treatment: help to make sure they get the answer right at the first try; or else assurance that they may leave the problem untouched.

One problem asks pupils to calculate the force on a jumping man who lands carelessly without bending his knees. There is a good demonstration to illustrate that on the next page.

* Giving the answer sometimes makes a problem more enquiring. Professional examiners know this; giving more data does not always make a question easier. It may warn the candidate against a vague answer and pin him down to answering an essential enquiry.

Demonstration 22 The jumping man: force of impact on floor

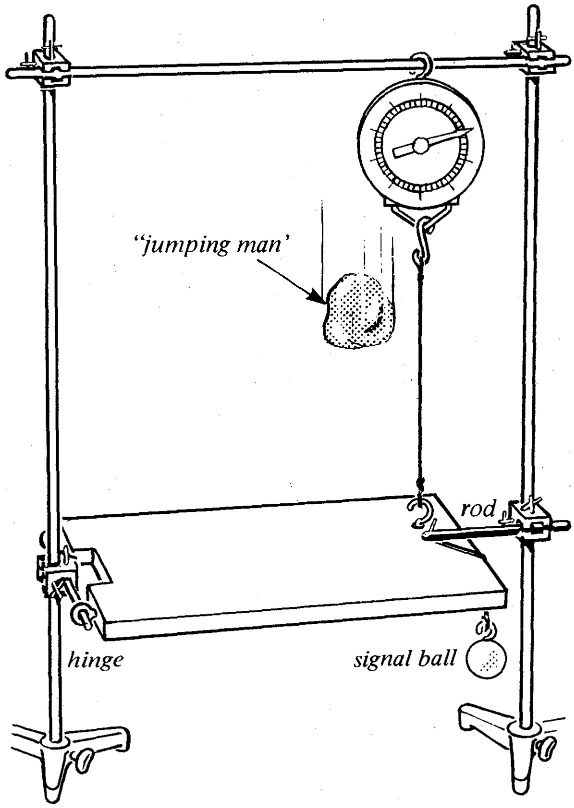
Apparatus

for (a)

1 ball of Plasticine (about $\frac{1}{2}$ kg)	item 570
1 domestic balance (5 kg)	20 or 206

for (b)

1 demonstration spring balance (50N)	85 or 212
1 2-cm metal ball with hook	131A
2 retort stands	503
3 retort stand rods	504
4 bosses	505
1 ball of Plasticine (about $\frac{1}{2}$ kg)	570
1 pivoted platform (see below)	
2 steel rods (see below)	55D
string, wire, or cord	



Preparation

Platform Set up a pivoted platform of wood about 25 cm long, 5 to 10 cm wide and about 1 cm thick. Its weight is to be neglected so it should not be heavy. Fix two screw-hooks in one end to form a hinge on a steel rod (about 10 cm long, 6 mm diam) held horizontally in a boss.

Opposing pull Near the other end of the platform fit another screw hook to hang the platform by a wire or cord from a demonstration spring balance fixed above it.

Signal ball Arrange a short steel rod, held by a boss, as a stop, so that the platform is pulled up against it when the spring balance is under tension. Tie a short piece of string to a metal ball and trap the end of the string between the rod and the platform. This provides a 'signal ball' which will fall when the platform moves downwards and there is no longer a force between platform and rod.

The tension in the wire can be altered within wide limits by adjusting the height of the spring balance.

Procedure

a. As a preliminary simple illustration drop a ball of Plasticine on to the domestic balance.

b. For the main experiment, first show the WEIGHT of the Plasticine ball (which represents the jumping man). Place it on the platform near the suspending wire, and point out the change of balance reading.

Then drop the ball onto the table from increasing heights until a height is reached from which the ball releases the signal ball. (Drop the Plasticine near to the hook attached to the spring balance and always on the same point on the platform.)

Reasoning

When the table is pushed down enough to release the signal ball, there is no force between the rod R and the platform. Then the force of impact P must equal or just exceed the upward pull T of the spring balance (neglecting the weight of the beam). This needs careful explanation or the experiment loses its point.

A suitable value for the tension in the spring balance is 30 newtons. Then the force of impact P exceeds 30N when the signal ball is released.

Another problem asks about the force between boot and ball when a player kicks a football. The data in such problems may seem arbitrary—'how do we know the kick lasted $\frac{1}{100}$ sec?' So here is a demonstration in which measurements are made.

Demonstration 23 Kicking a football: estimate of force *(OPTIONAL)*

Apparatus

1 scaler	item 130/1
1 football (rugby type not suitable)	
2 4-metre flexible leads ‡	
1 stopwatch or stopclock	507
1 balance	206 (or 20)
Plasticine	570
aluminium foil ‡‡	571
Sellotape	92N

‡ The flexible leads should be 2 amp PVC covered stranded wire or 26 SWG insulated single copper wire.

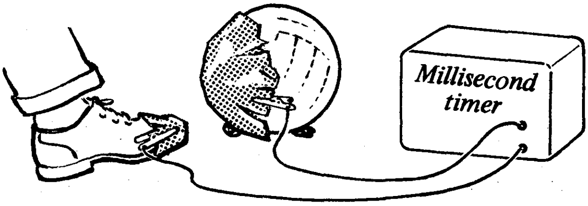
‡‡ The foil should be cooking thickness or slightly thinner. A 15-cm square of foil and a 10-cm square are needed.

Procedure

Choose a pupil to kick the football. Sellotape a 10-cm square of foil to the toe of his shoe.

Sellotape a 15-cm square of foil to the lower half of the football and place it on three small lumps of Plasticine to support it at rest.

Connect the two foils to the long leads by crocodile clips. Fit the other ends of the leads *loosely* in the 'make-to-count' sockets of the scaler so that they will come out easily in the event of an accident. (It is as well to have a pupil holding the scaler on the bench.) Flexible leads must be arranged so that the period of contact finishes before the ball pulls the foil away from the crocodile clip.

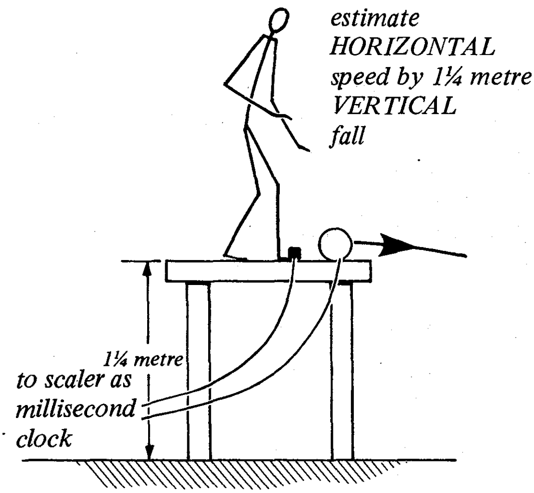


The kicker kicks the ball and the scaler records the time-of-contact between toe and ball.

To calculate the force, we need to know the ball's mass and its speed after the kick has ended.

For a very rough measure of the final speed estimate the time of flight of a ball kicked with medium force down a 10- to 20-metre corridor (or even a 10-metre lab) by using a stopwatch with a count-down procedure.

For a better estimate, place kicker and ball on a high table, $1\frac{1}{4}$ metres above the floor. If the kick projects it *horizontally*, the ball will take $\frac{1}{2}$ second in its accelerated vertical motion to reach the floor. Measure the distance the ball travels horizontally, and assume it took $\frac{1}{2}$ second to do this.



Alternatively, if pupils are familiar with multiflash technique, use that and photograph the ball in flight with a metre rule near its path.

Each pupil should record the measurements and calculate the force during contact, using $F = ma$, as in the calculation for the jumping man. Or, for an easier, clearer calculation, postpone this experiment until *momentum* calculations are discussed in Chapter 4 and use $F \times t$ = change of mv.

If the experiment is postponed to a late stage in Chapter 4 conservation of momentum could be put to use in estimating the final speed of the ball. The separate experiment for that is popular and rather noisy. Place a large carton on roller skates, with one face open to receive the ball. A pupil kicks the ball, more or less horizontally, into the carton. Arrange flaps of cardboard in the box to trap the ball, so that it does not bounce out again. Then all the ball's horizontal momentum is shared with the box, which slides away slowly. Measure the speed of the box (roughly) and calculate the original speed of the ball. See the sketch in *Pupil's Text 4*, page 85.

BERNOULLI PARADOXES AS EXAMPLES OF NEWTON'S LAW II

Although the Bernoulli effects are of interest in discussing aeroplane flight and a number of other things, they form a small part of physics which we could well leave out. So far as factual knowledge is concerned, we do not mention them here for any special interest in the principle itself; but we treat them to show the essence of scientific explanation—linking strange phenomena to a simple law which pupils already know—Newton's Second Law of Motion.

Bernoulli demonstrations Show a number of amusing 'Bernoulli effects', and then explain how all such effects are really only examples of Newton's Law II.

Description of equipment for Bernoulli experiments

Bernoulli-effects kit containing:	item 232
1 glass tube with jet	232/A
1 polystyrene ball (diam about 4 cm)	232/B (=3B)
2 table tennis balls	232/C
1 funnel	232/D
1 cardboard tube (30–50 cm, diam about 5 cm)	232/E
1 cork or rubber stopper for cardboard tube	232/F
6 cork balls (diam 2–3 cm)	232/G
1 small cardboard tube (20–30 cm, diam $2\frac{1}{2}$ to $3\frac{1}{2}$ cm)	232/H
1 metre elastic tape (2–3 cm wide)	232/I
1 metre cloth tape (2–3 cm wide)	232/J
steel wool for 'birds nest'	232/K
Also needed	
1 metre rubber tube to fit glass jet and funnel	
1 adapter to connect rubber tube to blower	
2 10-cm G-clamps	44/1
1 air blower ‡	165

‡A toy air blower will *not* suffice for these experiments. A hair dryer (with the heating element turned off) will suffice for 25a but may not be enough for 25c. A vacuum cleaner is needed which can take a flexible hose on the 'blowing' end (as opposed to the 'sucking' end).

Class Expt 24 Bernoulli paradox with two sheets of paper

Apparatus

sheets of ordinary paper

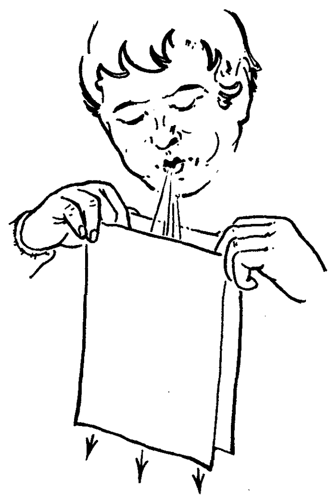
Procedure

Pupils follow these instructions:

* * * * *

Hold two sheets of paper 2 or 3 centimetres apart. Hold the top edges with two hands and let the sheets hang down. Keep them apart with two fingers between them. Bend your head down and hold the sheets just under your mouth.

Blow down into the space between them.



Some squeaker toys make their noise with blades like those two sheets of paper. And your own vocal cords act in the same way when you talk or sing.

* * * * *

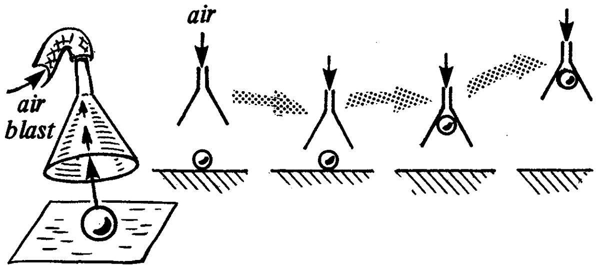
Demonstration 25 Surprising Bernoulli effects

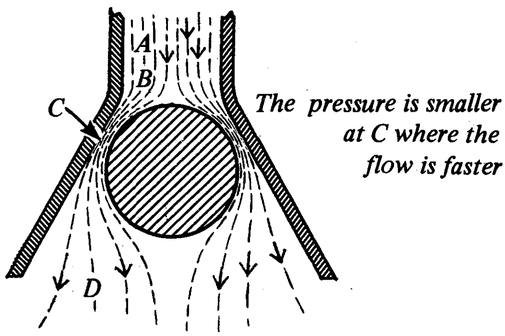
Apparatus

1 air blower (see note)	item 165
1 Bernoulli effects kit (see box opposite)	232
1 metre rubber tube to fit glass jet and funnel	
1 adapter to connect rubber tube to blower	
2 10-cm G-clamps	44/1

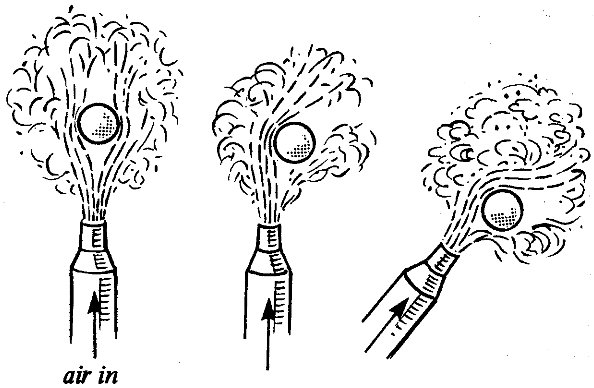
Procedure

a. Ball picked up by a funnel Connect the funnel to the air blower by rubber tubing. Put a light ball on the table and bring the funnel down over it. The air blast through the funnel picks up the ball and holds it. (*Pupils' Text 4* discusses the 'explanation'.)





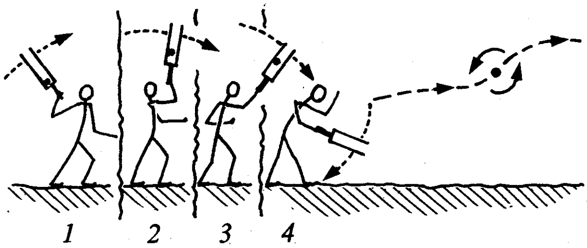
Streamlines of air around ball in funnel



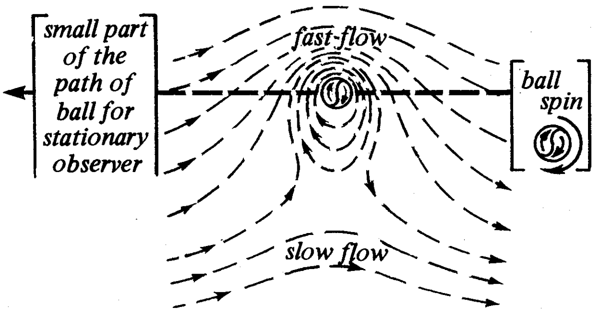
b. Ball supported by air jet Connect the blower by rubber tube to a glass tube with a narrow opening at the end. Place a light ball above the air jet. It will continue to be 'held' supported even if the jet is tilted over.

c. Ball supported by a water jet. Place a table tennis ball in a vertical jet of water.

Experiments involving spin



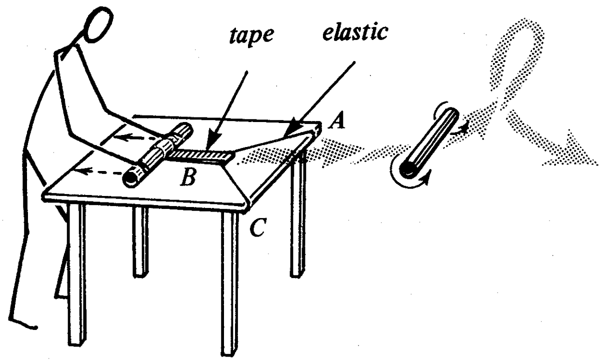
d. Spinning ball (Optional) Place a light ball, e.g. a $2\frac{1}{2}$-cm diameter ball of cork (used by fishermen) in a long cardboard tube closed at the lower end. Hold the tube upright with the lower end in one hand. Hold it with arm outstretched upward and slightly backward. Then sweep the outstretched arm quickly forward and down. During this motion, the ball rolls out along the *upper* inside surface of the tube and emerges spinning fast around a horizontal axis. The ball's flight will then show a marked upward curve. This demonstration needs practice. It may help to line the tube with fine sandpaper, to make sure the ball rolls rather than slides.



streamlines of air past a spinning ball

e. Spinning cylinder (Optional) Fix a metre of elastic to the bench at A and C. At its centre, B, attach a length of cloth tape. Wrap the other end of the tape several times round the middle of the small light cardboard tube (preferably with its ends closed by paper and Sellotape). Roll the tube along the bench to continue the wrapping until all the tape has been coiled up round it. Pull the tube back across the bench, thereby stretching the elastic.

Release the tube: the elastic catapults it forward, and the tape sets it spinning at the same time. The tube moves in a 'distorted' path. The Bernoulli forces may even be big enough to make the tube loop the loop.



Class Expt 26 How do aeroplanes stay up? Another Bernoulli effect

Apparatus

sheets of paper (about 10 cm × 20–30 cm)

Procedure

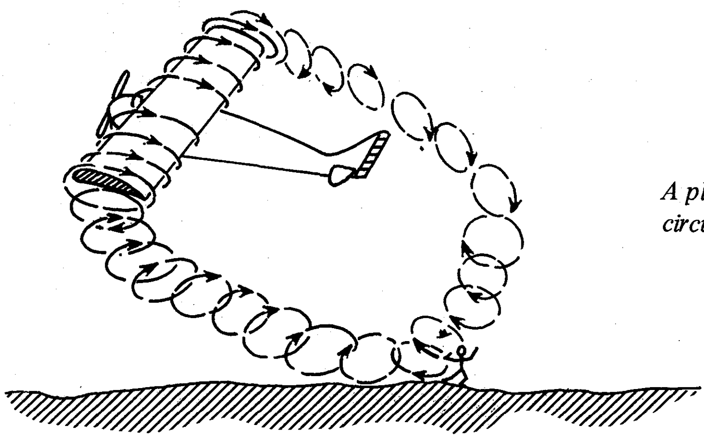
Pupils follow these instructions.

*   *   *   *   *

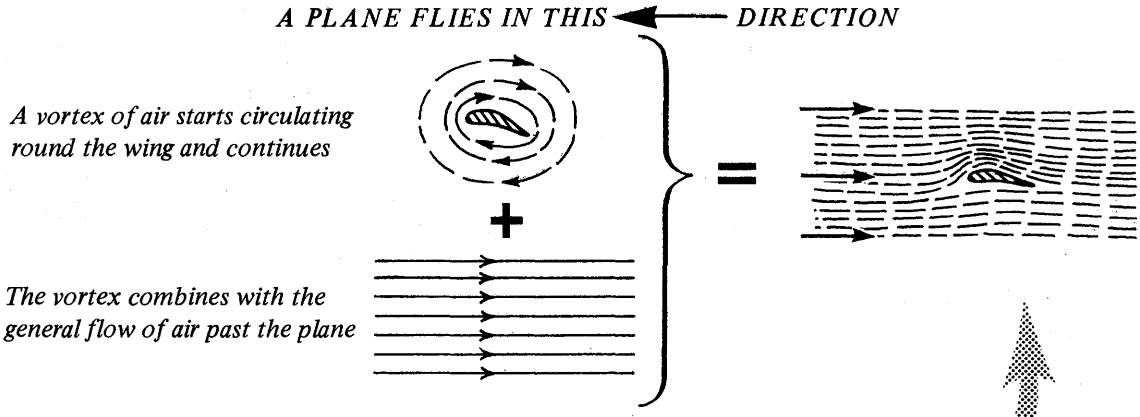
Hold one end of a long narrow sheet of paper with both hands. Bring that end against your chin, just under your lips. (The paper should be fairly thin so that the other end sags under its own weight.) Blow a steady blast of air *over the top of the paper.*

This shows the way an aeroplane wing is given 'lift', so that the plane can fly.

*   *   *   *   *



A plane taking off starts a vortex of circulating air (as in a smoke-ring)



The combined pattern is like this with faster flow above the wing. Hence less pressure above; and therefore LIFT

Explanation by single assertion These and other surprising effects can all be 'explained' by appealing to the qualitative form of Bernoulli's principle: that *in flow of fluid the pressure is smaller where the flow is faster*.

Although it is an 'explanation' that links together several phenomena which look dissimilar, it is not a very good scientific explanation in this form because it drags in a new, unexpected principle. If we could link this principle in turn to something familiar, we should feel we were much more powerful scientists. We should be farther from superstition and nearer to the assurance of Lucretius that 'science frees men from the terror of the gods.' We can do that.

Explanation by linkage to earlier knowledge First show one more experiment which illustrates the principle itself and shows its connection with familiar mechanics. We drive a rapid flow of water through a wide glass tube, which has a narrower section. Vertical standpipes rise from each section to show the pressure there.

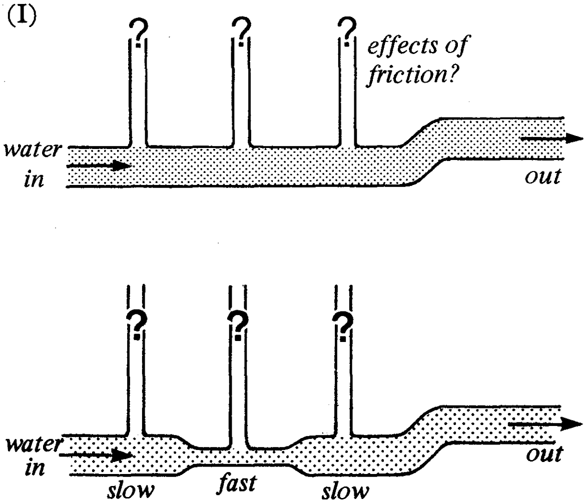
With a fast flow of water pupils will see that the pressure is much lower in the narrow section where the speed is greater.

Demonstration 27 To explain Bernoulli's principle by water flow through a tube

Apparatus

1 pair of 'Bernoulli' tubes (must be wide)	item 143
1 translucent screen	46/1
1 lamp for translucent screen	46/2
steel wool for 'birds-nest'	232K
1 adapter (rubber tube to wide entry tube)	
(dye)	

(I)



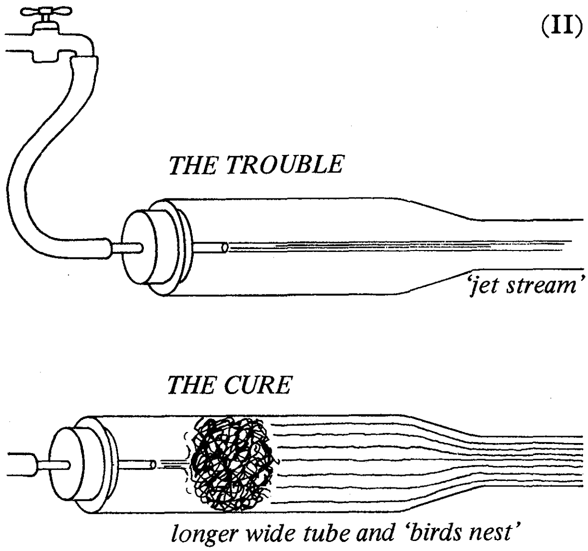
Special warnings

1. For this important demonstration to succeed at all it is essential to construct the apparatus of large tubes, so that water-friction is relatively unimportant. (Some equipment previously supplied to schools has failed on this account.) The wide tubes must have at least 2 cm diameter, and the narrow section at least 1 cm diameter. The stand-pipes can, of course, have small bore; but their connections to the main tubes should be shaped to avoid interfering at all with the flow.

2. Even with large pipes, the demonstration will fail unless there is a full flow of water *through the whole cross-section of the entry pipe*. If the water is brought from a tap through a narrow rubber tube to a glass tube in a cork in the wide entry pipe, there will be a narrow jet-stream of water in the wide pipe, with stagnant water around it—and no Bernoulli effect can be expected.

If the water is not supplied through wide tubing like a garden hose, but comes through ordinary narrow tubing, *it must be made strongly turbulent and spread over the wide tube* by being driven through a 'birds-nest' of wire gauze or steel wool as it enters the apparatus. Then the demonstration will not only show a Bernoulli paradox but will provide the essential evidence for the general explanation by Newton's Law II.

(II)



If tube (I) is wide, the stand-pipes will show that the pressure differences due to water-friction are small.

In tube (II), provided the flow is sufficiently great, pupils will see that where the water passes through the narrower tube, and the flow is necessarily faster, the pressure is reduced.

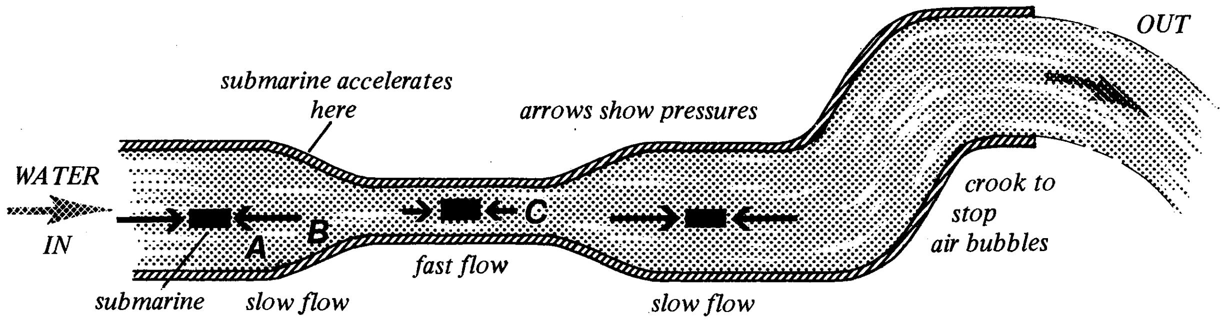
If there is not a striking reduction, either the flow is too slow or the birds-nest is insufficient to spread the entering flow across the wide tube.

Procedure

Set up the tubes and connect each in turn to the tap.

Silhouette each tube by placing it in front of the translucent screen with a lamp behind.

For a large class it may be better to colour the water. Place some potassium permanganate or solid dye in a small cloth bag in the wide entry tube.



Explanation by Newton's Law II Much as in *Pupils' Text 4*:

* * * * *

In the wide part A the water flows along quite fast. What must it do in the narrow part C? Remember that the same amount of water has to get through the narrow part as the wide part, A. The water must be moving *faster* in the narrow part. Then when it gets to the next wide part it must move slower again.

Imagine we put a little submarine in the water, to move along with the water itself. The submarine might be a small oblong block of wood of the same density as water.

Suppose the submarine has flat ends. In the wide tube A, the submarine is carried along fairly slowly with the water. It does not change its motion. In the narrow part C, the submarine is carried along much faster, and it does not change its fast motion.

But in the knee, B, where the tube is narrowing, the water has to change from slow flow to faster flow and *the little submarine must change speed too*. In the knee *it must accelerate*.

Where the submarine is accelerating, there must be a resultant forward force pushing it to accelerate it.

The submarine has water all around it and the only agent to push it is water exerting a pressure on it. The water pushing on the sides of the submarine cannot help it forwards or backwards. The water pushing on the back end of the submarine pushes it forwards, and the water pressing on the front end of the submarine pushes it backwards. When the submarine is in the knee those two pushes must be unequal. The submarine *must* feel a bigger pressure of water on its back end than on its front end.

Therefore the pressure must be bigger in the wide part than in the narrow part of the tube.

Now forget about the submarine and think of the water itself. In going from wide to narrow it changes from slow flow to fast, it *accelerates*. There must be a force to make it accelerate and that force is provided by water pressure. The water pressure must be bigger in the wide part than in the narrow part. Therefore: faster flow, lower pressure.

Thus the Bernoulli effects are only a matter of force being needed to accelerate the fluid from the slow-moving regions to the fast-moving regions: just a matter of $F = ma$.

* * * * *

(The more usual account of the effects and the derivation of the Bernoulli principle by considerations of energy is much more artificial, because it makes us invent 'pressure energy' and that would not be helpful here.)

Outcome In all this, we want pupils above all to feel that they are exploring the way in which a force changes motion, and makes things go faster and faster, finding that a slow job if there is a great deal of matter to be speeded up. This understanding is more important than ability to calculate the force in newtons that will do a particular job, or to calculate the acceleration produced by a given load hung on a string and pulling a given trolley along a level table. Pupils should emerge with a clear feeling that they have explored and learned a good deal about force and mass and motion.

{**Philosophy of Newton's Laws** There are some definitions and assumptions interwoven with all experimental illustrations of Newton's Laws of Motion: for example, the description of our system of force-measurement, which we encourage our pupils to take for granted; and rules that forces acting side by side are additive, and that masses piled up together are additive. (See the note on 'interaction' in the General Introduction issued with *Teachers' Guide 3*.) These are not physical weaknesses in Newton's Laws, they are simply proper parts of his description of nature. We should not worry pupils or even ourselves about these philosophical matters; and yet we should keep in the back of our mind just enough hint of doubt to prevent us telling pupils that they have proved that Newton's Laws are wholly right. In fact, the Laws are right (subject to some relativistic modification) but they are partly right by definition and partly right because they do describe nature—and the pupils' experiments illustrate the latter connection.}

CHAPTER 3

NEWTON'S FIRST LAW

Mass and inertia; notes on mass

NEWTON'S FIRST LAW OF MOTION

Although we regard Newton's First Law as a special case of the Second Law, pupils do not recognise it as that—any more than did philosophers at the time of Galileo and Newton who found in it a change of view concerning the Moon and planets—a shattering denial of the current astronomical explanation. It seems wise to discuss the First Law with pupils as a separate topic.

How much we have to explain and whether we show the experiments mentioned here will depend on the treatment in Year 3.

Common-sense and Law I Ask pupils about an object moving straight along without changing its speed. What force does that steady motion need to maintain it? If pupils say 'no force', at once let them push a chair or table along a rough floor and ask whether they really call that no force. In other words, start by respecting the common-sense view which Aristotle postulated: that steady motion requires a steady force. That is true when the moving object pushes against an invisible opposition such as that provided by friction.

Some questions for the space age Ask: 'Is the Moon slowing down appreciably, as it goes round and round the Earth?' 'How can you know whether it is?'

'Does a space traveller have to keep his rockets going when he is far out in space? Why? Why not?'

'Does a molecule of air in the room move slower and slower, although there is no driving force to keep it going? (If molecules of air do move slower and slower, through some mysterious friction, where will all the air be in a few minutes from now?)'

Frictionless motion Then in contrast show a demonstration of motion continuing with no force either way along the motion.

Hovercraft for Newton's First Law We can demonstrate Newton's First Law—which Galileo foreshadowed in his thought experiment—by a 'hovercraft' experiment with solid carbon dioxide to eliminate friction. We consider it essential for pupils to see one form of this frictionless-motion demonstration, and not just hear about it.

This experiment is so important as well as so delightful, that we hope teachers and their schools will be willing to take the trouble and bear the cost of obtaining a large block of 'dry ice' or solid CO_2. (The small quantities of solid CO_2 obtained from a portable cylinder will *not* suffice for this.)

A large block will be delivered to the nearest railway station if the suppliers are notified a week beforehand. It will cost several pounds and there will be some trouble, of telephoning to order it and of fetching it from the station; but the demonstration is very impressive. (See the list of supply depots in Appendix 5.)

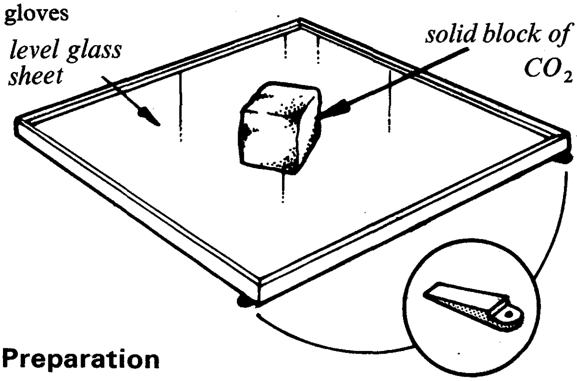
The block of solid CO_2 will coast almost without friction on a smooth clean glass plate (and so will the ring pucks). At first sight, the cost of the glass plate may seem an unnecessary expense; in fact it makes all the difference to the success of this startling experiment. Ordinary table tops are neither flat enough nor smooth enough. Even a formica top is usually unsatisfactory.

Unless all the class saw one of these demonstrations in Year 3, we hope one can be shown now.

Demonstration 28a The coasting iceberg

Apparatus

1 large block of solid CO_2	
from Edinburgh CO_2 Kit	item 95
large glass plate	95A
4 wedges for levelling plate	95B
window cleaning liquid (or methylated spirits) for cleaning plate	
blanket or newspaper for wrapping the block	
thick metal plate ($\frac{1}{2}$ to 2 cm thick, preferably aluminium or copper for 'ironing' the base of the block)	
gloves	



Preparation

Levelling is very important. Use the rubber wedges and shims of paper. The motion of a CO_2 block itself is the most sensitive test of levelling.

It is essential to clean the glass plate thoroughly before use.

Cut a block roughly, with a hacksaw, say 15 cm by 15 cm by 10–15 cm. Make one face of the block flat by sliding it on the thick metal plate. *Test the levelling of the glass sheet with the block itself.*

Wrap the block in blanket or newspaper to keep it from collecting water until it is used.

Procedure

Put the block on the glass plate and give it a small push. It will coast freely as a 'hovercraft'. To show that the block is not just coasting down a slight slope start it moving the opposite way.

If pupils wish to try pushing the block, make sure they wear gloves or protect their fingers in some other way. The cold solid CO_2 will produce a blister like a burn.

If the block rests for long at one place on the glass sheet it will cool the glass so much that moisture will soon condense there. This will make a sticky patch which will spoil motion across the sheet.

As an alternative, ring pucks that coast on the glass sheet need only a little dry ice—enough can be manufactured in the lab with CO_2 from a cylinder.

Ring hovercraft are used later in two-dimensional collisions. So, if pupils have not seen them in Year 3, this provides a good introduction.

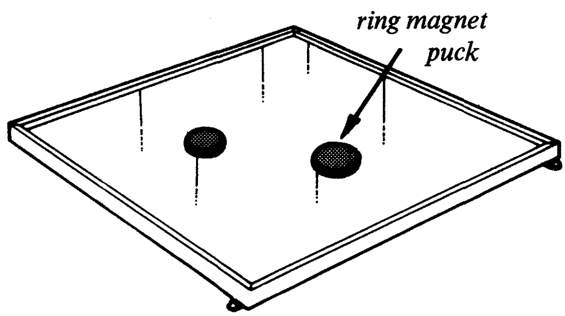
Demonstration 28b Ring hovercraft

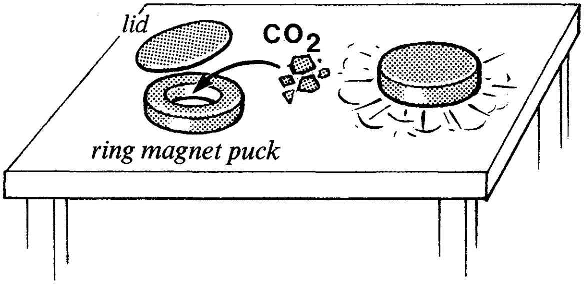
Apparatus

from Edinburgh CO_2 kit	item 95
large glass plate	95A
4 wedges	95B
1 ring puck ‡	95C
window cleaning liquid or methylated spirits) for cleaning plate	
1 CO_2 cylinder ‡‡	19/1
1 dry ice attachment and cloth	19/2

‡A ring puck is a metal ring with a lid of metal or cardboard. Solid CO_2 placed under the lid provides a stream of gas so that the ring coasts with practically no friction. The magnetic pucks have poles on their flat faces: their repulsion is used for elastic collisions in a later demonstration.

‡‡The special cylinder supplied with the attachment is a siphon type. Keep it upright. If the cylinder is the ordinary fire-extinguisher type, invert it.





Preparation

Clean the large glass plate very carefully and level it. This is essential.

Procedure

Make a few cm^3 of solid CO_2 'snow' with the attachment on the cylinder. Fold the cloth to double thickness and hold it over the nozzle. A few seconds' burst of CO_2 will provide enough CO_2 'snow'.

Place a small piece of solid CO_2 under the puck. After a moment or two a stream of gas runs out under the edges of the ring, keeping the puck supported.

Give the puck a push and let pupils watch it coasting. To show that it is not just coasting downhill, give it a push the opposite way.

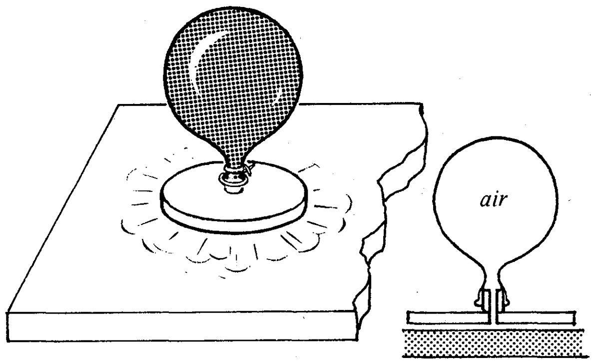
Demonstration 28c Frictionless motion *(ECONOMY ALTERNATIVE: NOT RECOMMENDED)*

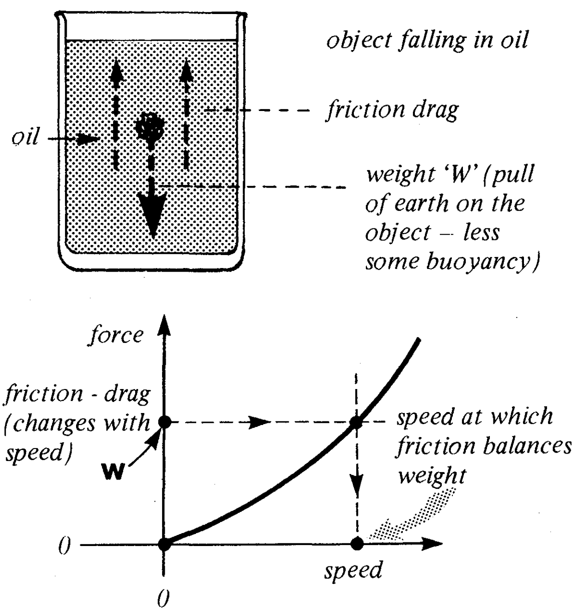
The ring pucks of 28b can be supported by a thin layer of polystyrene beads spread over the glass sheet. There is little friction but the beads escape and are a great nuisance. They cling easily to hair and clothes and can be a hazard on the floor. Only if it proves quite imposible to show CO_2 support should this alternative be used.

Class Expt 29 Home-made hovercraft: 'poor man's puck' *(OPTIONAL EXTRA)*

A delightful qualitative experiment for class or home can be done with an ordinary balloon supplying a simple puck.

Drill a small hole in the centre of a smooth disc of plywood of diameter 15 cm. Glue to that a short piece of tubing of any kind that will fit in the balloon's neck. Inflate the balloon; attach it to the tube and place this puck on any smooth table.

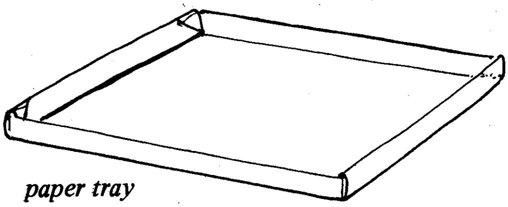




Motion against variable friction With 'fluid friction', the motion takes on a very interesting characteristic: since fluid friction increases when speed increases* a body being pulled against fluid friction accelerates until the friction-drag reaches a size that balances the pulling force, and then there is a constant 'terminal velocity'.

Remind pupils of that behaviour, which they may have met in earlier years. Show again an object falling in viscous liquid.

* But not in direct proportion, in most cases. The commonest form of fluid resistance varies as v^2. For example: a paper tray falling in air; or, roughly, some cases of drag on an aeroplane's wing.



(about 20cm x 15cm, edges 1cm high)

First let a small paper tray fall in air. Then show small steel balls falling in viscous oil; or polystyrene balls in water. Pupils should see that the object falls with constant speed, (after a short initial acceleration). Soon we shall interpret that constant-velocity motion as due to friction forces (acting upwards) just balancing the pull of gravity downwards (less the buoyancy of the surrounding fluid).

Fluid friction and the terminal velocity resulting from it were offered in Year 2 with styrocell beads falling in water. Repeat that here; or, as a variant, drop steel balls in a glass tube containing motor oil.

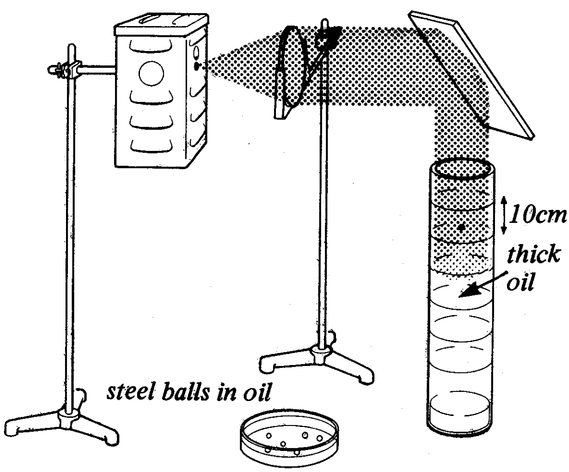
Demonstration 30 The invisible parachute: terminal velocity

Apparatus

Glass tube, $\frac{3}{4}$ metre long, 5 cm or more diam. ‡	item 131F
Ball-bearing balls ($1\frac{1}{2}$ mm, 3 mm, 6 mm diam.)	131G
Chinagraph pencil (or black masking tape)	543
1 large positive lens ($f \approx 10$ cm)	93B
1 holder for lens	124/2
1 compact light source	21
1 L.T. variable voltage supply	59
3 retort stands and bosses	503,504,505
1 plane mirror and clamp	116, 506
small dish of oil	
motor oil (or glycerine) 2 litres‡‡	240

‡ The diameter of the tube should be at least 5 cm so that the falling balls will be far from the sides.

‡‡ The oil should be as light in colour as possible. Glycerine is better, because it is clear, but it is expensive. Medicinal mineral oil is clear but its viscosity is too low for a satisfactory demonstration.



Preparation

Place the balls in a small dish of oil before use, so that each ball is already oily and thus does not carry an air bubble with it.

Mark the outside of the tube at 10-cm intervals with a Chinagraph pencil (or with strips of black tape).

Special illumination is helpful. If the room can be partially darkened, and if the oil is of a light colour so that it does not absorb much light, the best illumination is a beam from a very bright source directed vertically down the tube by a mirror.

Make sure the bottom of the tube is firmly closed so that it cannot give way and make a messy flood. The bottom may be a closed glass end, preferably rounded. Place a piece of cloth in it to break the fall of balls. Or use a rubber stopper; but that *must* be wired to the tube to prevent it from oozing out. (If the rubber stopper carries a glass stopcock for draining, the tap of the stopcock must also be wired in (or spring loaded) to prevent accident.)

Procedure

(i) Explain that the balls are going to fall in a very 'stodgy' liquid—or drop one ball in the oil and then an equal ball in a tall jar of water.

(ii) Drop balls of different sizes for pupils to watch.

(iii) Drop a ball and ask pupils to watch the motion carefully. As the falling ball comes level with each mark on the tube give a signal such as a handclap. (Stopwatches should *not* be used—this is a quick experiment for an important general idea.)

A magnet will help to remove accumulated balls from the tube.

If a supply of (small) balls is left beside the tube in a shallow dish of oil, pupils may try the experiment themselves as they pass by.

FORCE AND CONSTANT VELOCITY: DISCUSSION CONTINUED

Now we must face the conflict between the fact that a steady push is needed to keep a chair sliding along the floor and the fact that no force is needed to maintain some other steady motions.

By now, pupils should be ready to point out that in the case of the chair on the floor there is more than just the force exerted by the person pushing it. There is also the force of friction dragging backwards. In *Pupils' Text 4* we ask:

> 'How do you know friction is acting on the chair? You know that you have to push the chair. You know that the floor is rough, so you think you may be pushing against something we call friction. But how do you really know the force of friction is there?'

{Note that we are still asking questions, respecting pupils' reactions, and discussing matters; we are most anxious *not* to begin formal Newtonian mechanics with strong assertions that must be swallowed unthinkingly.}

Feeling friction forces There are two ways in which pupils can experience the friction for themselves: by having their skin as the surface that is moving along a rough floor or table; by letting their skin be the 'floor' across which something rough is dragged.

{The pupil who points out that those two ways are really the same is already developing a sense of Galilean relativity, and deserves immediate praise.}

Friction and heat Some teachers like to comment at this point on the heat developed when friction forces drag along surfaces. And some consider that this heat which can be felt makes a fine starting point for a general study of heat; so they suggest we should diverge on a discussion of heat at this point. Others prefer to continue the approach to Newton's Laws of Motion.

In any case, if pupils raise this question of heat, there should certainly be some immediate discussion.

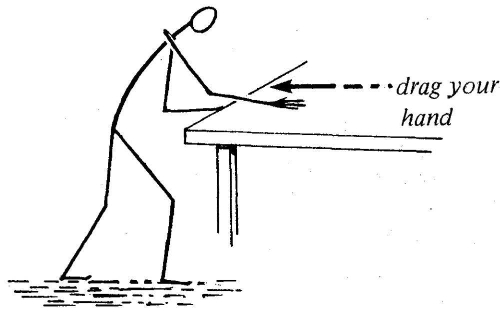
Class Expt 31 Feeling friction yourself

Procedure

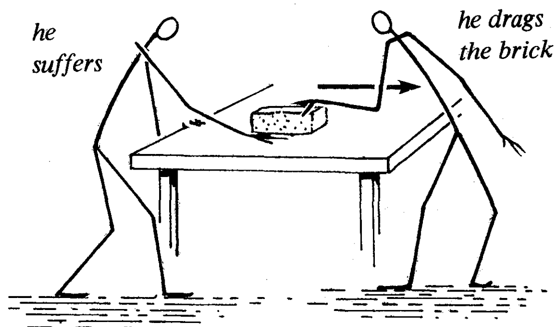
Pupils follow these instructions:

* * * * *

a. To feel friction for yourself, put your hand loosely on the table, palm down, and drag it along.



Then ask a neighbour to hold your wrist and drag your hand along the table. That may make it easier for you to pay attention to the forces at the surface.

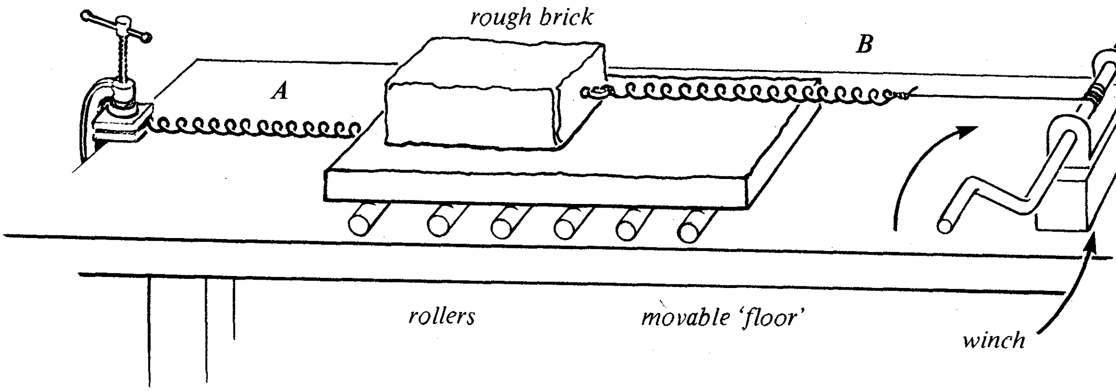


b. Now use your skin as the table top. Place your hand, *palm up* on the table and hold it still there. Let a neighbour place a heavy load (a brick or a pile of books) on your upturned hand. What do you feel when your neighbour drags that load along your hand?

* * * * *

Balancing forces Then offer a demonstration of a rough object being pulled along on a floor with the floor itself on rollers. Pupils see an object moving at constant velocity while it is pulled by equal-and-opposite forces.

Demonstration 32a Balancing forces? (Illustration of Newton's First Law)



Apparatus

1 large smooth plank	item 55A
1 crank assembly	55E
10 steel rods as rollers	55D
1 wooden 'brick'	
2 retort stands, bosses and clamps	503–506
3 G-clamps	44/2
2 expendable springs ‡	2A
thread	

‡ For this demonstration to be worth anything, the measurements of the two forces must be clearly visible for comparison by all members of the class. Small tubular spring balances would be hopelessly unconvincing to pupils at a distance—the teacher might just as well teach the experiment by asserting the result. Large dial spring balances (with the dials facing the pupils) would be excellent for the visible comparison; but arranging and supporting them suitably would be difficult—the brick might topple over, or fail to move straight ahead.

Therefore we suggest the crude but clear comparison of two simple spiral springs. With the two forces involved the springs will stretch enough to provide visible measures of the forces. If pupils see beforehand that the chosen springs are matched in length and force-constant, they can judge in the demonstration whether the forces are equal in magnitude.

(Nevertheless, if a teacher likes to experiment with two dial balances, a good Russian design is now available, imported and sold in pairs for much less than item 85.)

Procedure

Put the rollers on the table. Place the plank on the rollers so that it can move freely along with little friction.

To keep the plank from moving along, tether it with spring A to a clamp at one end of the table. The stretch of A will indicate the restraining pull on the plank. This also shows the force exerted on the plank by the brick as it is dragged along. *Thus the plank acts as a stationary floor with a device for measuring the brick's friction drag on it.*

Attach an *equal* second spring, B, to a hook on the end of the brick. Run a horizontal thread from the other end of spring B to the crank assembly which is clamped at the other end of the table.

The stretch of B will indicate the pull that the winching thread exerts on the brick.

Winch the brick *steadily* along the plank by turning the crank. Pupils compare the length of the two springs to see whether the two forces are equal in size.

This is only an *illustration* of the general idea of Newton's First Law. It is certainly not proof. However it is a comforting experiment,* even if it is very rough. It may seem a pointless experiment; but, to young scientists, it resolves a very serious puzzle. They need to be assured that we can have constant velocity not only out in space or in special frictionless hovercraft, but in cases where there are large forces acting, *provided those forces happen to balance.***

* If we take a stern philosophical view and think out what is happening in terms of Newton's First Law, with Newton's Third Law treated as an accounting rule, we come upon grave doubts. We grow less and less sure what we are really measuring or demonstrating.

We can even convince ourselves that the whole demonstration is a swindle. It is not, because it is a demonstration of a real event in the physical world and it does supply some information to people who might have expected a different result. Therefore, it does convey some knowledge and it should be shown.

** Here, the two forces are *seen* to balance if the brick is winched along at constant speed. So this looks like a direct illustration of Newton's First Law.

In the next experiment, the two forces are pre-arranged to balance, without reference to Law I, by choosing pulling loads which are (almost) equal—then pupils *see* constant speed.

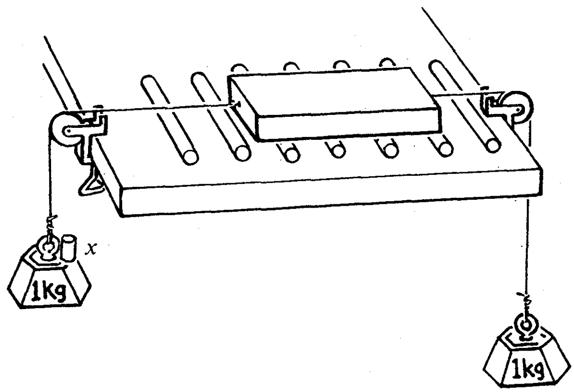
In other cases like hauling up a load on a string at constant speed, we *assert* that the string's tension is equal and opposite to the load's weight. It is difficult to demonstrate this without assuming what we want to show.

We might note in passing that physicists often take for granted an implied property that strings adjust their tension to balance the pull exerted on them. A real string makes that adjustment by stretching a little; if tension increases with stretch, that suffices—whether the string follows Hooke's Law or not.

Demonstration 32b Steady motion: balancing forces?

Apparatus

1 large smooth plank	item 55A
10 steel rods	55D
2 single pulleys on clamps	40
2 1-kilogram loads	32
1 small weight hanger with 10-gram slotted weights	31/1
string	



Preparation

Arrange the apparatus as in the sketch. A large smooth plank forms a massive 'trolley' that can run freely on rollers on the table.

Run a horizontal cord out from each end of the plank to the end of the table, where it hangs over a small pulley and carries a kilogram load—then those loads at the two ends pull the plank in opposite directions.

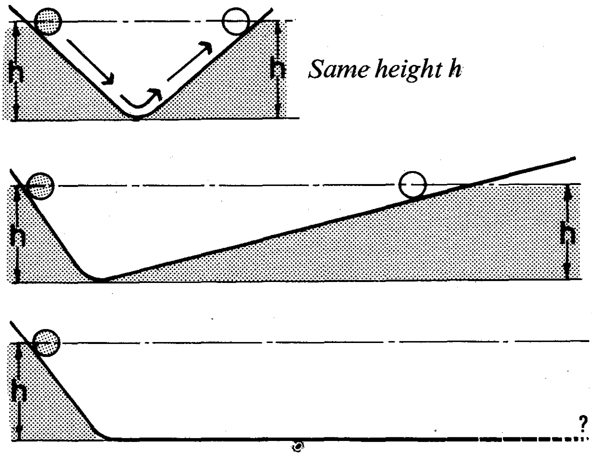
Arrange the lengths of the cords so that when the kilogram at one end is on the floor, the kilogram at the other end is almost at bench height.

Procedure

Show pupils the arrangement. Ask what are the sizes of the pulls. Then add a *small* extra load to the upper kilogram. That additional load should be such that the plank moves along on its rollers at almost constant velocity and does not continue to accelerate. A load of 50 grams is usually sufficient. Pupils watch the motion.

Discuss the interpretation.

† Galileo's argument leading to Newton's First Law Remind pupils of Galileo's downhill-and-uphill argument (described in Year 3). Illustrate it; then show Galileo's frictionless invention.



Galileo assured himself, by drawing upon his common-sense knowledge of nature, that a ball rolling down one hill and up another would, apart from friction troubles, reach the same height on the opposite hill as its starting height. He believed that this must happen *whatever the slopes of the hills might be*. Then he extrapolated to the special case of a ball rolling down one hill and meeting another 'hill' consisting of a level plain*, a hill that would never reach the same height. He concluded that the ball would never stop moving. In this way, Galileo arrived at Newton's Law I by a 'thought experiment'.

Demonstration 33 Downhill-and-uphill motion: Galileo's guess

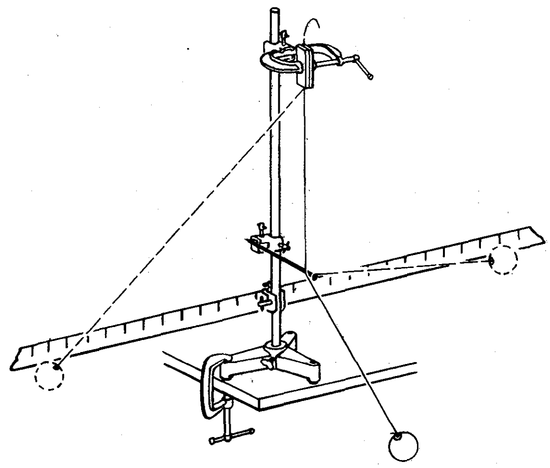
Apparatus and Procedure

See Demonstration 63 in *Teachers' Guide 3*.

* A puzzle for Galileo and for our pupils: would the ball go *straight on and on* along a tangent, or *on and on round the world*?

Relativity reminds us that we developed Newton's Laws of Motion because our experiments are conducted in an (almost) inertial frame. So our question here asks, 'Which will look more like an inertial frame?'

Demonstration 34 Galileo's frictionless invention: pin-and-pendulum experiment



Apparatus and Procedure

See Demonstration 64 in *Teachers' Guide 3*.

COMMENTS ON NEWTON'S FIRST LAW

Formal statement of Law I? If pupils are to be given a semi-formal statement of Newton's First Law, it helps them if we insert the essential word 'resultant'. When we say 'resultant force' in that Law, the Law makes sense. Otherwise it has that rarified form which seems to apply only to outer space.

We need a name for the *vector sum* of all the forces acting on the body. Law I applies to cases where that sum is zero. And the force in Law II is that vector sum when it is not zero. The name 'total force' is not suitable, because it has another technical meaning. The name 'unbalanced force' seems to us poor, because it suggests there is something a little strange or inferior about that force.

The names 'net force' and 'resultant force' are suitable; here we choose the old-fashioned word '*RESULTANT*'. We use it to mean the effective sum: *that single force which would, for most purposes, replace all the actual forces together*.

Inertia Again, in discussing the other aspect of Newton's First Law, the inertial property of matter, we should be very careful never to speak of a force 'overcoming inertia', as if inertia were a sort of internal armed guard, which once vanquished allows a frictionless life! Even the smallest *resultant* force maintains an acceleration.

{It looks as if we could substantiate Newton's First Law of Motion by experiments with spring balances. However, a very careful examination of the underlying logic involved suggests that all we really do when we state Newton's First Law is to describe a force. We say, 'When there is no force we see uniform velocity; when there is a push or a pull we see acceleration. When we cannot see whether there is a *(resultant)* force, we look at the motion and decide whether there is any acceleration. Then we think we know whether there is a force on the object.'!}

{Although that seems a depressing analysis, there is still some practical knowledge of nature therein; we can link 'no force' with 'leave a thing completely alone' and therefore expect a space traveller to continue to move with constant speed in a straight line if he is far away from any disturbing influences that we can see or think of.}

{And there is some knowledge of real nature in the inertial property of matter: the property of opposing change-of-motion, of continuing to move along when we leave it alone. Therefore, we urge teachers to keep Newton's First Law as a separate law and not just as a case of Law II—as it is now fashionable to call Newton's Law I. In our teaching we may, like Newton, find Law I worth stating clearly. Newton himself was trying to extend mechanics from Earth to sky, from common knowledge of motion to the whole solar system. He established an entirely new way of treating mechanics; a treatment that was partially built by Galileo from the work of a few earlier scientists, and was brought out into the open by Newton as a reforming influence on the whole of medieval physics.}

THE CONCEPT OF MASS

Mass Now let us return to mass in our programme; this concept receives more and more attention from year to year. If we can succeed in giving pupils some feeling for this concept by Year 5, we shall have made an important contribution to their education.

Mass is a difficult, strange, sophisticated concept; but it is now so important in science that we should do our best to build up a sense of understanding it.

Pupils should have seen demonstrations in Year 3 to illustrate the idea of mass, or give meaning to the word inertia. Whether we can take for granted an understanding of mass from Year 3 or must start afresh and discuss the idea carefully, will vary greatly from class to class and pupil to pupil.

Because the concept is a difficult one it is probably best to discuss mass fully now, even giving some of the old demonstrations though maintaining a reassuring claim that this is 'revision'.

On the other hand, we shall not make this difficult concept of mass clearer by a boring routine repetition of the work of Year 3. Therefore, discussion and experiments are only mentioned here so that teachers may choose any that seem suitable.

Two special illustrations offer great help to a variety of pupils:

I. Put a heavy pupil and a light one on roller skates. Give each a push.

Also ask them to face each other, extend hands as buffers and push apart.

If roller skates are available, and discipline is not in danger, this demonstration will teach a lot, and needs no comment.

II. Show a short film of astronauts performing in a '*g*-free' situation. The moral: *mass* is still there.

Descriptions of mass Experiments show that the more trolleys we have piled together the bigger the force we need for a given acceleration; or, the less acceleration we get for some standard pull. There is something about these chunks of matter that makes them 'difficult to accelerate'—not difficult in the sense of a rough backward drag of friction to be opposed, but a sluggishness, a slowness in getting moving. *The effect of even the smallest resultant force is slow but sure; we get any amount of motion if we wait for a long enough time.* (That last is an important point for some schemes of rocket-propulsion in outer space.)

It may help to coin some slang descriptions of mass such as 'unaccelerability', 'difficultness of getting it going', and perhaps even 'massiveness'. (The origin of the word *mass*, a *lump of dough*, is suggestive.)

Professional scientists use the word 'inertia' to describe this property, but in teaching boys and girls that might be no more than taking refuge behind a pompous long word. Pupils soon learn to avoid answering 'friction' and to be very careful not to mention 'weight' but to use 'inertia' as a magic word that will get good marks. That has little to do with understanding this important concept.

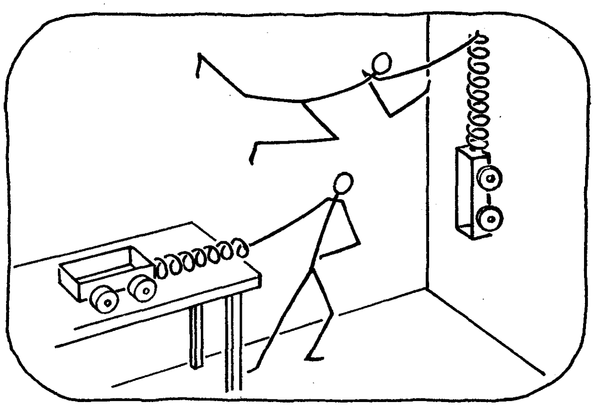
{To say that 'mass is energy' or something to that effect, in a bow to relativity, will not help at all here; and many a physicist would consider that wording a misleading version of the safer statement, 'energy has mass'.}

{**Mass and weight in engineering** Many an engineer in earlier generations could afford to ignore *mass* as a separate concept. He was concerned with the *weight* of the bridge and the *weight* of the load on the bridge, which increased the stress in the members of the bridge. He could afford to measure forces in kg-weight, or pounds-weight, and use them in his own version of Newton's Laws of Motion.}

{In this age of nuclear power and space flight, the modern engineer needs mass in its own right. He learns, as every physicist must do, to regard mass as an important fundamental property of matter and energy, quite different from the pull of the Earth on everything that possesses mass.}

Newton himself described mass as 'quantity of matter'. It is fashionable today to laugh at Newton's statement, saying that it only referred 'mass' to another word 'matter'. However, Newton was a wise man, writing first for himself and then publicly for his contemporaries; and his description was probably a teaching device to make something clearer to people who were struggling with a new idea. We might try that phrase with our pupils too. When we consider atoms we may well think mass is a measure of 'quantity of matter', particularly if we measure it rather loosely by counting nucleons.

A useful 'thought experiment' for our teaching here, would be to imagine experimenters in a space ship in outer space, free from a gravitational field, trying to pull a trolley along 'horizontally', on a frictionless table. They use a spring to exert the pull. Then they hang the trolley 'vertically' on the same spring, holding the top of



the spring in one hand. They accelerate the trolley again by pulling it upwards with the spring. For the same stretch of spring in each case, what differences will they notice between the two motions?

By drawing a 'leading diagram' on the blackboard one can mislead pupils temporarily into believing that vertical and horizontal have a real meaning and are different. When they realise they have been tricked, they will be left with a feeling that the mass is still there needing a force to accelerate it and gaining the same acceleration with the same force *whatever the direction of pull.*

Inertia balance Pupils should play with a 'wig-wag' machine, preferably as a simple class experiment. We want them to gain a clearer feeling for mass by watching the machine, rather than try to use it as a scheme for *measuring* mass.* We may say it is a to-and-fro pushing device and the slowness of the motion tells us something about the 'unshoveability' of the load we place on it.

Gravity plays no part whatever in the operation of this machine; it is a true inertia balance.

* For their own interest, rather than for teaching pupils in this year, teachers might try guessing at the relationship between load and period by some general thinking. The device has mass and springiness, so it is equivalent to a load attached to a spring which obeys Hooke's Law. We expect S.H.M. and we predict a relationship between period and load. Experiments with the device will confirm the prediction, provided we ascribe to the platform itself a certain equivalent mass. Plotting a suitable graph will give a straight line which will indicate that equivalent mass by its intercept.

EXPERIMENTS TO ILLUSTRATE THE CONCEPT OF MASS AND INERTIA

At this stage, we should not just talk about mass as a theoretical concept; we should repeat quickly some experiments from Year 3.

Pupils can gain a practical feeling for mass and inertia by pushing two large tins hung as pendulums, one full of sand, the other empty.

Pupils' Demonstration 35 Feeling inertia

Apparatus

2 tin cans
sand
string

The tin cans should look identical. Treacle tins will suffice; but the larger the cans the more effective the experiment.

Preparation

Suspend the cans with strings as long as possible. Long strings from the ceiling are best of all. Leave one can empty, fill the other with sand.

Procedure

Pupils follow these instructions:

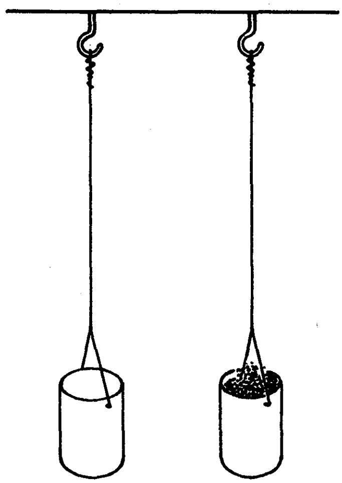
* * * * *

Try pushing each can in turn to feel the force needed to give a can some motion. Give each can a knuckle-flip and watch the effect.

Also try stopping the cans when they are moving.

* * * * *

Point out that there is no question of resistance by friction in this case: it is the MASS of the can of sand that makes it slow to get moving—not impossible, as friction might make it, but slow.



Ask why safety-belts are worn in cars, asking what happens to the non-belted passenger on the back seat when a car suddenly starts, stops or goes round a sharp corner. This could lead later to a discussion of motion in a circle—but do not embark on that now or the class will get seriously entangled with 'centrifugal force'.

Class Expt 36 The 'wig-wag': inertia balance

Purpose

AIMS: This is a qualitative experiment with two uses:

I To help pupils to understand mass. They see the effect of the same set of forces on different masses, without any interference from gravity.

II For interested pupils, a special extension of the experiment makes the distinction between mass and weight still clearer.

Pupils see what happens when they 'take some of the WEIGHT off the machine' without changing the MASS. This extension, which is a delight to teachers, may prove confusing to some pupils; so it should not be allowed to take a prominent place.

Apparatus

either 1 inertia balance kit (for 16 pairs) item 146
or 16 home-made balances‡ (see description in box)
32 or more equal loads, e.g. $\frac{1}{2}$ kg‡‡

‡The home-made form works just as well. The differences between the two forms are in cost, appearance and pupils' attitude.

‡‡The maximum safe load depends on the strength of the blades. It should be possible to add enough to slow the vibrations to half the original frequency, or even less.

Procedure

a. *General experiment* Pupils follow these instructions:

* * * * *

Clamp one end of the wig-wag to the table with G-clamps so that the blades project out horizontally from the table. The other end of the wig-wag acts as a platform that can vibrate to and fro horizontally.

Make sure the fixed end is clamped firmly to the table. Otherwise energy will leak away and the motion will die down very fast.

If the loads rattle or jump about, try holding them with a rubber band.

Pull the platform to one side; release it and watch it vibrating.

Then increase the mass by adding loads to the platform.

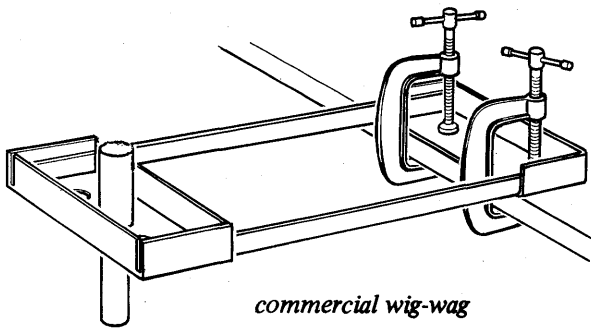
* * * * *

b. *Optional extension for a fast group* The blades push the platform and its load to and fro, and the slowness of the oscillations is a measure of the MASS of the moving system: it does not depend on its WEIGHT. Pupils make sure of that by 'taking away some of the WEIGHT without changing the MASS'.

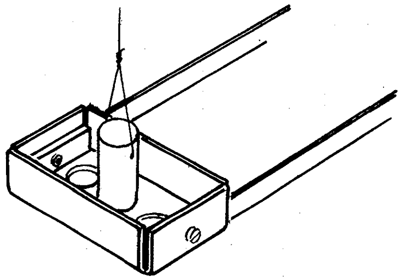
They do this by pulling the added load upwards with a thread, so that most of the weight of that load is borne by the thread and only a little of it supported by the moving platform—and yet the moving platform carries the full mass of the load to and fro with it.

While the pupil carries some of the weight by pulling it upwards he must move his hand to and fro in phase with the motion of the platform to keep the thread vertical.

Description of inertia balance (wig-wag) apparatus



commercial wig-wag



THE BALANCE is a platform carried by a pair of springy blades which swing it to and fro horizontally with S.H.M. The remote ends of the springs are anchored firmly to the lab table with a G-clamp.

Loads placed on the platform change the period of oscillation visibly. Since the motion is in a horizontal plane, the WEIGHT of the platform and loads does not affect the period; but the MASS does. (In fact T^2 varies as the total effective mass; but that relationship is not used now.)

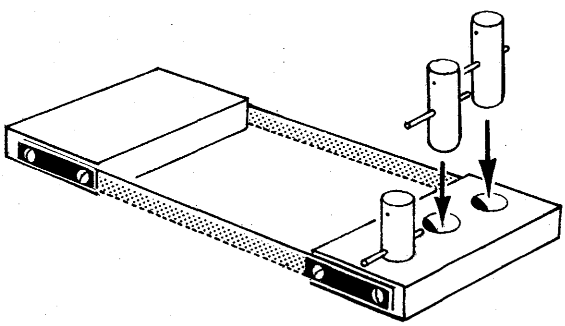
Thus when pupils find that their machine pushes the load to and fro they can think of it as indicating 'unpushability' or 'inertia' or mass. Since we need the help of the machine in teaching the *general* concept of mass it is best to make the machine look simple and general by assembling a home-made form for each pair of pupils. Buying saves trouble but bought ones may give pupils a stronger impression of being made as 'special devices' to 'prove' science—which is bad for our reputation. In some manufactured forms the platform has holes drilled in it to receive special loads that slip in and are prevented by a peg from falling right through. This makes it easier to add loads without their sliding about on the platform; and those special loads can be provided with holes for a suspending thread. However, these refinements are unfortunate—a useful device assembled from common components has then become a 'special' gadget which may add to a misleading view of science. Ordinary 'weights' as loads would make it seem more like an experiment put together to conduct a useful test.

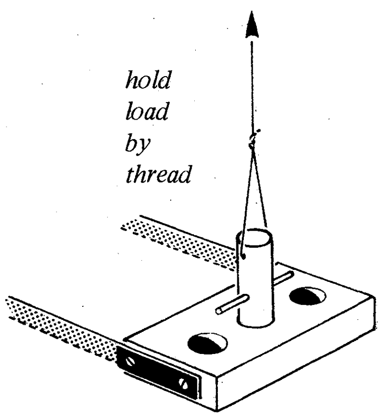
HOMEMADE FORM For a homemade wig-wag, use two hack-saw blades or equivalent lengths of metal strip placed parallel. Place a block of wood between them at one end, to serve as anchorage to be clamped to the table. Place a similar block of wood between them at the other end, to act as a platform to carry the loads.

It might seem simplest to attach the blades to the blocks of wood by driving screws into the blocks through holes in the blades. That would leave some play between the blades and the wood blocks as the blades bend to and fro, and there would be considerable damping. To avoid spoiling the machine's behaviour by damping, it is essential to clamp each blade very firmly *on both* faces. Where the blade is clamped against a wooden block, a small block of wood or metal should be placed outside the blade, flush with the main block, so that the blade emerges as if from the well-matched jaws of a vice. Then screws may be driven through the small block and blade into the big block; or, if the machine is to be assembled only temporarily, a large G-clamp may be used to clamp together small blocks and both blades and the large block, in a multiple sandwich.

LOADS Each balance needs several loads, which should *look* equal and be approximately equal. The size of the load should be chosen so that the balance can carry at least three of them without overload: $\frac{1}{2}$-kg loads will be suitable for most designs. A total of 32 will suffice since pupil-groups can borrow.

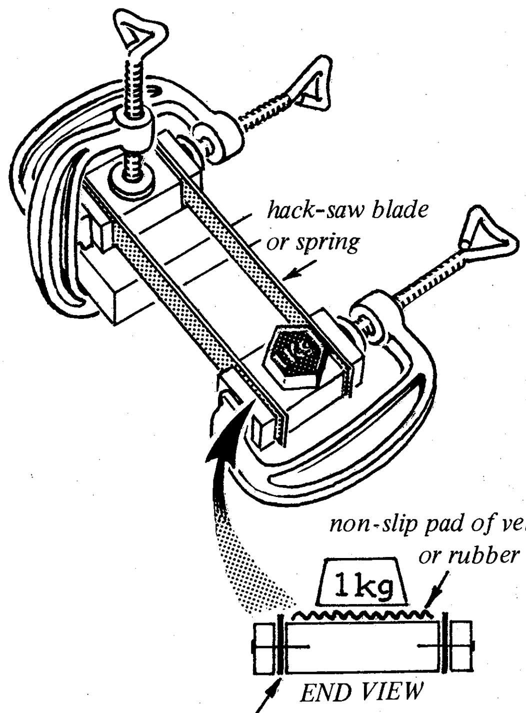
A GOOD HOME-MADE FORM

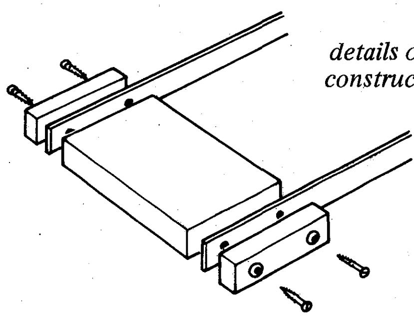




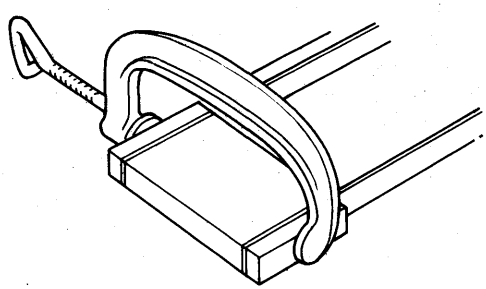
Similar screwing or clamping is needed at the other end.

ANOTHER GOOD HOME-MADE FORM





or use a clamp



Inertia tricks *(Optional)* In discussing inertia teachers may like to give pupils some illustrations that were suggested in Year 3. (They were optional then and we do not recommend them strongly here either.)

To young people these traditional experiments are delightful tricks rather than exhibits of inertia so we suggest them mainly for fun.

Class Expt 37 Tricks that illustrate inertia *(OPTIONAL)*

Apparatus

a pile of books

b 5 wooden blocks (say 10 cm × $7\frac{1}{2}$ cm × 5 cm) ‡
mallet or hammer

c coin, card, tumbler

d	retort stand, boss, clamp	item 503–506
	thin sewing thread	
	large mass (1 kg or more)	32
	G-clamps	44/1

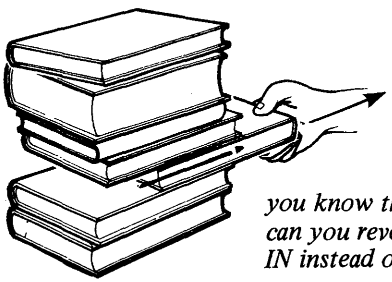
e thin sewing thread (breaking force say a few newtons)
small mass, 1 gram

‡ The bricks should be smooth blocks of wood, say 10 cm × $1\frac{1}{2}$ cm × 5 cm high, with the heights carefully made the same. Their edges and corners should be rounded.

Procedure

Pupils follow these instructions:

* * * * *



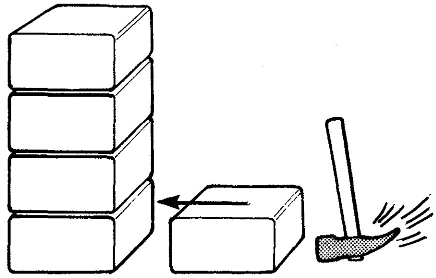
a. *The simplest trick* Pull one book out from the middle of a pile of books.

b. *A reverse form of (a)* Push a wooden brick in at the bottom of a pile of similar bricks.

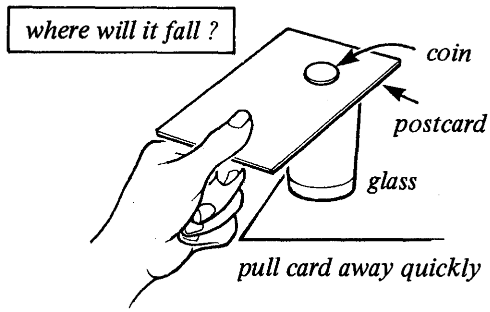
Build a pile of 4 bricks, then push a fifth brick, quickly, straight at the bottom brick of the pile. The fifth brick goes in and the bottom brick goes out.

This is most dramatic if the fifth brick is projected along the table towards the pile by a 'croquet hit' from a small mallet.

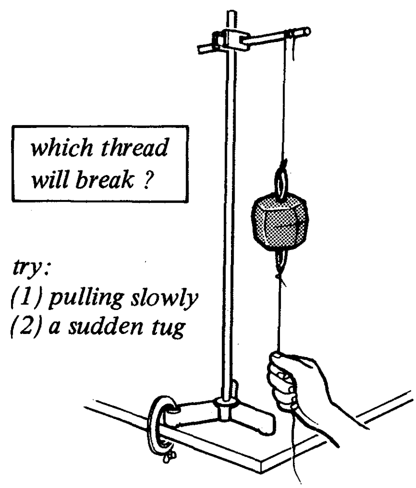
Repeat, using the ejected brick as the projectile.



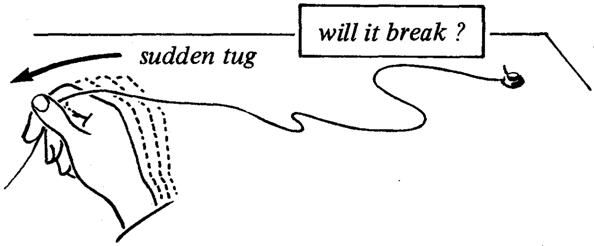
c. *A coin on a card on a glass* Whip away the card and the coin falls into the glass.



d. *Breaking threads* A thread is hung from the bottom of a load which itself hangs on a thread. A steady pull on the lower thread breaks the upper thread but a sudden snatch on the lower thread breaks the lower one!



To make the underlying paradox specially clear, use the same kind of thread throughout, but have a single upper thread and two or three strands in parallel for the lower thread.



e. *Breaking a thread* A very small mass (1 gram) is tied to the end of a long loose thread and placed on the table. Although the breaking strength of that thread is many hundreds of grams and it carries only one gram loose on the end, it can be broken by a *very sudden* jerk of the other end. (Strong sewing thread needs 5 or 10 grams for this to succeed.)

Note: Some commentary is given in *Teachers' Guide 3.*

NOTES ON MASS

Units for mass Hold two single kilograms that look the same and are each labelled 1 kg, and ask if they have the same mass. Pupils may say that they are made of equal volumes of the same materials so they are the same. Explain that any serious enquiry must refer back ultimately to the world's standard kilogram kept at Sèvres in France. Since we cannot borrow that, we have to use a copy which has been tested in many stages against the standard.

Measurement of mass The fully legitimate methods of measuring a mass by comparing it with a standard kilogram make use of the part played by m in $F = ma$. Here are three versions, *A*, *B*, and *C*.

A. Place first the unknown mass then the standard kilogram on a trolley and accelerate each in turn with the same force. (Allow for the mass of the trolley by a third measurement.) Alternatively adjust the unknown till it matches the kilogram—each then having the same acceleration.

B. Place the two masses to be compared on trolleys that are joined by a stretched spring. Release the trolleys, and argue from their meeting-point. Although that demonstration, ending with an exciting collision, seems a good test, it probably distracts attention and had better wait until we discuss momentum-changes in collisions. It involves Law III explicitly.

C. Place each mass in turn on a wig-wag. Make suitable measurements. (This needs an additional observation of the wig-wag's motion when empty.)

However, those methods are clumsy in practice and neither pupils nor teachers will enjoy using one of them when the mass of something is to be measured. Of course *we* just weigh them—and risk the confusion of ideas. That is method D.

We expect very few pupils will see that this quick precise method D needs justification. But teachers may wish to keep the argument in mind.

D. Comparison of masses by weighing involves two experiments *(i)* and *(ii)*, and an argument *(iii)*.

(i) Place the object to be weighed on one pan of an equal-arm balance. Add standard masses to the other pan until the two loads match. Then we say that the Earth pulls equally on the two loads.

(ii) Then do a second experiment—equally essential, though we often just imagine it—free fall. Release both loads and show that they fall with the *same* acceleration, g.

(iii) Therefore, with $F = ma$ in mind, we say F_1 and F_2 are the same—from *(i)*. And a_1 and a_2 are the same—each is g, from *(ii)*. And therefore m_1 and m_2 are the same.

Vocabulary: Mass, weight and weighing Tradition and common usage give us a confusing vocabulary. Even if we are meticulous and call a box of weights a *box of masses* we are defeated by the verb to *weigh*.

In writing questions and discussions the editors have tried to use a consistent compromise:

Nouns: for MASS (measured in kg) we either say *mass* or evade a label; for WEIGHT (measured in newtons) we say *weight* or *pull-of-the-Earth*.

Verb: for measuring or comparing *masses* we say *weigh*—despite the misfortune. When we want the weight (or pull-of-the-Earth) we avoid the direct verb and say measure the weight of . . .

A FURTHER NOTE: TWO KINDS OF MASS

{**Inertial mass and gravitational mass** In using method *(D.)*, we made an enormous jump, between inertial *mass* and *gravitational mass*. We should not point out the difference to pupils, who will just assume the two kinds are the same. They will be in good company: Newton used that assumption too. In teaching, however, we should keep the argument and its history in mind. Here is a short account:}

{Two very important statements concerning free fall are given to us:

(i) From Galileo and Newton: *'All objects fall with the same acceleration, in a vacuum.'*

(ii) From Einstein, three centuries later: 'There are two different kinds of mass, inertial mass—the m_I in $F = m_I a$— and gravitational mass—the m_G in $F = Gm_G \, M/d^2$.'}

{We should be rash to take it for granted that the amount-of-stuff-to-be-accelerated and the amount-of-stuff-to-be-pulled-on-by-a-gravitational-field are the same physical quantities.}

{It is the fact in *(i)* that answers the doubt in *(ii)*: free fall, with the same g for all, shows that m_G and m_I *are the same*—and thus forms a basis for General Relativity.}

{Only in the last hundred years did physicists realise the extraordinary significance of the common property of falling bodies—the result of the experiment that Galileo did not show*—that a large mass and a small mass both fall with the same acceleration g. The Earth's gravitational field pulls the iron ball with a much bigger force but the material to be moved is bigger in the same proportion, so the acceleration is the same for both.}

{Now analyse more carefully. The pull of the Earth's field is proportional to m_G (the m in $F = GmM/R^2$). The mass to be accelerated is m_I (the m in $F = ma$). Then we see that we have no guarantee (except from that vital experiment which shows g the same for all) that these two kinds of 'amount-of-stuff' are equal (or proportional) for all materials. We have no guarantee that a large chunk of aluminium and a small chunk of lead which are shown by trolley experiments to have the same inertia will also be pulled by the Earth with equal forces—*until we let them fall.*}

{For contrast, think of the 'amount of stuff' concerned with another physical property, heat capacity. Take these two lumps, aluminium and lead, which have the same inertia. If we say we expect them to contain the same amount of matter from the point of view of *warming-up when given a standard amount of heat*, we shall be gravely disappointed. If we insert no extra factor of specific heat capacity we shall find that the aluminium block seems to have six times as much matter-to-be-warmed-up as the lead block. However, it does happen in the construction of our universe that the mass which responds to gravitational fields and the mass which is involved in Newton's Second Law of Motion are proportional: and in fact we can use a kilogram as a unit for each.}

{We should not mention this distinction between inertial mass and gravitational mass to our pupils at all; but we should keep this discussion in the back of our own minds in teaching, because it will help us to avoid certain logical troubles.}

* Most historians of science say that Galileo did not give a public demonstration of dropping a large object and a small one from the top of the leaning tower of Pisa. They point out that, if he had done that, there would have been letters carrying the news all across Europe: and no such letters have been found. Of course he knew quite well what such a demonstration would show; and he quoted, in one of his dialogues, the small difference of fall that would be observed, between a wooden ball and an iron ball falling from a high tower.

CHAPTER 4

MOMENTUM CONSERVATION OF MOMENTUM

Newton's Law II in momentum form Newton's Law III and Momentum Conservation Experimental illustrations and uses

TREATMENT OF NEWTON'S LAW II BY MOMENTUM*

Algebra with constant acceleration Perhaps the clearest way to sum up and reinforce the knowledge that pupils have gained with these experiments is to express it in terms of momentum—that was Newton's own choice. In many cases a problem is easier to think about, and may be easier to work out, by saying that FORCE × TIME is change of MOMENTUM.

Then when we combine that with Newton's Law III we arrive at Conservation of Momentum as a very important general rule for dealing with mechanical systems.

The traditional way of changing to this form is to write:

$$F = ma = m(v-u)/t$$

therefore
$$\begin{aligned} Ft &= mv - mu \\ &= \text{final } mv - \text{initial } mv \\ &= \text{gain of momentum} \end{aligned}$$

Descriptive method For some pupils a slower, less algebraic introduction does better, with momentum appearing as the thing which must be provided by a force acting for a certain time. *Pupils' Text 4* offers a new start along those lines, leading to

THE FORCE × TIME = CHANGE OF MOMENTUM

This will seem to some pupils a long roundabout form of $F = ma$. But to others it may seem a more natural approach. And in any case we shall be glad to have this form for use in our later studies.

Momentum is a strange concept for most beginners, compared with acceleration, which seems more obvious to many. That is why we treated the example of the jumping man first by $F = ma$. Now pupils should try it again, using change of momentum. But, for momentum to become really important, we must wait for collisions, in which the various momentum-changes will always add up to zero. Then Conservation of Momentum will become very important as a universal rule in physics; so we are justified in starting now to build up a feeling for momentum.

As soon as we introduce momentum, we should warn pupils that there is another very useful quantity, kinetic energy. They must learn to distinguish clearly between mv which is a measure of FORCE multiplied by TIME, and $\frac{1}{2}mv^2$ which is distinctly different and which is a measure of FORCE multiplied by DISTANCE.

Pupils should look on momentum as a good way of specifying 'motion'. It tells us *how much material* is rushing along, combined with *how fast*

* As a beginning of dynamics we could follow Newton and start with $Ft = \triangle mv$ instead of $F = ma$. The concept of momentum is at least as easy for beginners to grasp as the concept of mass. The momentum approach makes a good start conceptually. However, experimental tests with trolleys and tape are much more confusing for beginners—the timer must record the time during which force is applied and then, further along the tape, the motion with constant speed.

it is rushing along. If we wish to stop a moving body we have to take away its momentum. The MOMENTUM that is to be removed tells us FORCE × TIME.

Examples of changing momentum Give pupils examples to show how, when a given amount of momentum has to be lost (or gained), we may have a choice between using a *large* force for a *short* time and using a *smaller* force for a *larger* time.

In landing on the floor after a jump, the jumper can decrease the force by lengthening his time-of-landing. (The earlier problem on this is offered again, now treated by momentum, in *Pupils' Text 4*, Chapter 4. Pupils should see Demonstration 22 now if they did not see it before.

In Demonstration 23 pupils make measurements to estimate the force exerted by a player's boot on a football. Here, too, the treatment by momentum is even clearer. See *Pupils' Text*, Chapter 4.

NEWTON'S LAW III AND CONSERVATION OF MOMENTUM

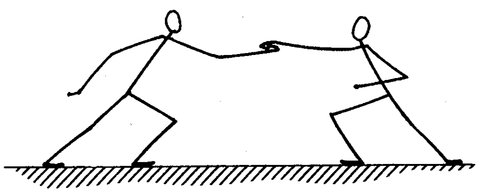
Pupils may have had a glimpse of Newton's Third Law of motion at some earlier stage, but now they need to know what it means and how to use it.

{The great French mathematician Henri Poincaré wrote a strong, convincing commentary on Law III in one of his general books on philosophy of science, *Science and Hypothesis*. He showed that the experiments usually quoted to 'prove' Law III by using spring balances, etc., cannot succeed in showing that action and reaction are necessarily equal. He decided that Law III is only a matter of definition, an 'accounting rule', chosen by us for our own convenience in expressing our knowledge of nature. We certainly should not mention this discussion to our pupils, but we should keep it in mind because it may restrain our comments somewhat when we are teaching.}

Demonstration 38 'If I pull you, you pull me; if I push you, you push me.' Newton's Third Law, Action = −Reaction

Procedure

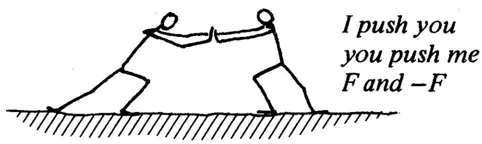
Ask a pupil to join in a demonstration. Say to him: 'Stand firmly opposite me and hook your right hand with mine. Pull.'



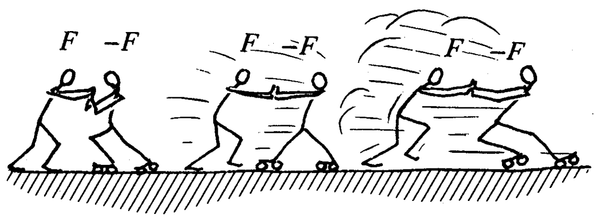
Suggested argument, as in *Pupils' Text*:

*   *   *   *   *

'Which way am I pulling him? Towards the blackboard, or away? And which way is he pulling me? (Away, towards the clock at the other end of the room.) Those two pulls do not cancel out and come to no pull at all. *I* can feel *his* pull quite well, and *he* can feel *my* pull. Only one of those pulls acts on him, *my pull* towards the blackboard. And only one of those pulls acts on me, *his pull* towards the clock.



Now pretend I *push* him instead of pulling him. 'The reason he does not accelerate towards the clock is because there is another, quite different, force dragging him in the opposite direction. His rough shoes on the rough floor stop him moving. The floor pushes him away from the clock with a friction force which happens to balance my push.



'If I pushed much harder, his friction could not match my push and he *would* start accelerating towards the clock. If he were on roller-skates he would accelerate even if I pushed gently. And I would have to run if I wanted to keep up that push. But while we were running, my push on him would be matched exactly by his push on me.

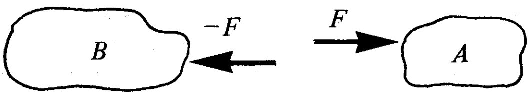
'The fact that I push him towards the clock *does not constitute a force on me* towards the clock. Of those two pushes, the only force on me is the push that he exerts on me, towards the blackboard.

'Newton decided that every pair of forces like that are equal and opposite: my push on him is exactly equal in size and opposite in direction to his push on me.

'That does not sound very interesting: but if we adopt it as a true working rule, it leads to a surprising prediction.'

* * * * *

{**False examples of Law III** We should be careful to avoid pointing to the wrong pair of forces as an example of Law III. We apply Newton's Third Law universally* to all interactions, whether the bodies are at rest, moving with constant velocity, or accelerating. In *all* cases the two forces, action and reaction, are a true reciprocal pair: the force exerted by body A on body B and the force exerted by B on A are equal and opposite.}

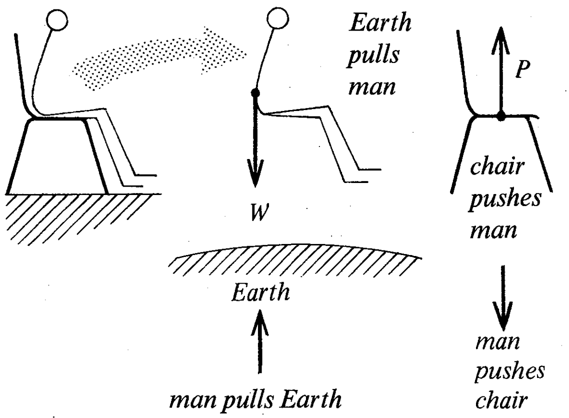


− F = force exerted on B by A   *F = force exerted on A by B*

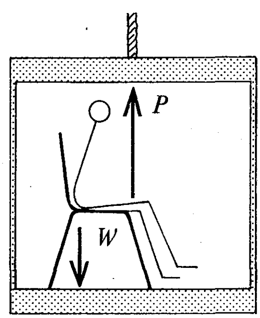
{However sometimes a text book takes a man at rest on a chair as an example and says:
'The man remains at rest: therefore the push up of the chair is equal and opposite to the weight of the man. (That is, of course, correct.) *Therefore*, in this case, action = −reaction.'

The *'therefore'* is nonsense. We do apply Newton's Third Law here, as everywhere else, but the two forces just quoted are not a reciprocal pair of action and reaction; and they are not necessarily equal and opposite.}

{The analysis is this: the push up (P) of the chair on the man *is* equal and opposite to the push down ($-P$) of the man on the chair. Those two forces form a Newton's Third Law pair. Also, the weight of the man (W) which is the downward pull of the Earth on him is equal and opposite to the upward pull ($-W$) of the man on the whole Earth, and those are another Newton's-Third-Law pair.}



{Each of the two last 'equal and opposite' remarks remains true *whatever happens*. But if we



lift is accelerating upwards. now P is greater than W

* Sometimes a paradoxical exception appears, in some arrangements involving electromagnetism. The forces between some pairs of 'agents' are *not* equal and opposite and it seems that momentum is *not* conserved. But we receive a reminder that electromagnetic momentum must also be allowed for; and then all is well.

allow the chair to accelerate upwards or downwards (e.g. in an accelerating lift*) a force of the first pair is no longer exactly balanced by a force of the second pair: the push up of the chair is no longer balanced by the pull down of gravity on the man. The true statement that when the man is in equilibrium those two forces, (P) and (W), do balance, is a statement belonging to Newton's Law I or II and not to Law III.**}

{We should not labour discussions of Law III with pupils who do not understand it or feel a need for it. However we should be careful not to store up misunderstandings which would be troublesome in future studies.}

CONSERVATION OF MOMENTUM

We assume Newton's Law III, apply it to an arbitrary collision (or other interaction) and argue thence that momentum is *ALWAYS* conserved. See *Pupils' Text 4*, for the argument.

Discuss the argument with pupils and make it clear that we expect to find the total momentum always the same, because in *any* kind of interaction whatsoever, the changes of momentum will happen in equal and opposite pairs. We point out that this is a remarkable new Law which helps us to keep track of any kind of event in which one thing exerts a force on another: 'The total momentum after the event is the same as the total momentum before.'

Of course, all the participants must be included in this. When a moving car comes to a stop it loses a lot of momentum, and that momentum seems to disappear altogether; but we believe that the Earth itself gains an equal amount of momentum. We can draw pictures of two things colliding and exchanging momentum without any gain or loss in the total, but in most experiments there is some friction which carries momentum off to the Earth, and then we find less momentum afterwards than before.

Pupils should see demonstrations in which there is no serious loss of momentum to the Earth; otherwise our story of conservation will seem unconvincing. (We believe the principle is just as true when momentum *is* lost to the Earth; but the account-keeping is harder to demonstrate experimentally.)

Although we should not start by insisting on it dogmatically to pupils, we should keep in mind ourselves the universal nature of the Conservation of Momentum. In *every* kind of action, in *any* kind of closed system, the total momentum remains the same. If we have a system which is not closed, one which has connections by forces to other bodies, including possibly the Earth, the total momentum of the system may change; but then too we expect to find conservation completely true when we keep account of the momentum changes in the other regions to which the system is connected. (We must include momentum of electromagnetic fields.)

Experiments on Conservation of Momentum The experiments to illustrate or test Conservation of Momentum should be class experiments as far as possible. Pupils should now have such skill with timers and tape that they can keep track of the motion of two trolleys by using two tapes at the same time. There should also be multiflash photographs of events in two dimensions—to yield a print for each pupil to analyse.

The experiments with trolleys and tape are of three kinds:

a. Collisions in which one of the objects is already moving before the collision;

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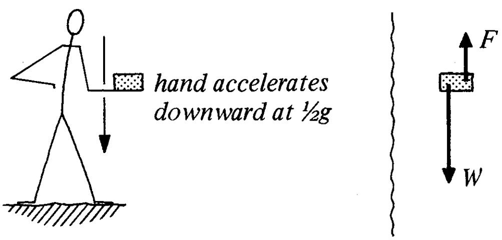
* Place a book on the palm of one hand, as a model of the man in the lift. Move the hand down with acceleration, say $\frac{1}{2}g$. The hand will feel a smaller pressure. The accelerating book no longer suffers equal and opposite forces, one of them the Earth's attraction and the other force the supporting push of the hand—but that inequality is no breach of Law III.



We need to say clearly, all over again, that the push up of the hand is a force on the book; but the fact that the book also pushes down on the hand, does *not* constitute a force on the book. Of those two forces, only one acts on the book, the upward force, and the book would accelerate if there were not some *other* force acting on it.

** This is an example of a 'dead-mouse answer' mentioned in the Appendix on Examinations in the General Introduction issued with *Teachers' Guide 3*.

b. collisions in which both bodies start at rest and are given equal and opposite lots of momentum by a spring or some other 'explosive agent'.

c. collisions in which both bodies start at rest and after developing some motion both come to rest again.

Of these, the first type seems to pupils a much more genuine exhibition of Conservation of Momentum: there is some visible momentum at the beginning and the same amount is there at the end. The other two types of experiment have the advantage of simpler measurements but they somehow seem obvious to pupils without being convincing: symmetry distracts attention from the essential conservation.

Choice of experiments Teachers will find a considerable variety of experiments suggested in the pages that follow. They should *not* try to carry out all these, or knowledge of momentum will seem a boring, troublesome business instead of a very interesting story. The more the teacher has succeeded in shortening the earlier studies of $F = ma$, the more time he can safely give to momentum experiments, without risk of boredom—and the better that will be.

However we do not want to use so many experiments to 'prove' that momentum is conserved that we never have time to show the principle being used. We shall put the principle to use in measuring the speed of an air gun bullet; and we then check the estimate by an alternative measurement that does not assume momentum conservation.

SYNOPSIS OF COLLISION EXPERIMENTS

(A) Head-on collision between moving trolley and trolley at rest This is a difficult but convincing experiment. Two trolleys are used, each carrying a tape.

One trolley, loaded to have a large mass, is given a push by hand and allowed to run at constant velocity along a friction-compensated runway until it hits the back end of a lighter trolley. The two trolleys do not stick together on collision, but the lighter trolley bounces forward with greater speed while the original moving one proceeds more slowly after it.

Pupils are dealing with the momentum of each trolley which should be constant before collision, and constant with a different value after collision. *Therefore there is no need here to paste up tape-charts.* Pupils simply measure the length of tape for a large, round-number of ticks, and work out the speed in centimetres per second or in centimetres per tentick—any unit will do as long as the same one is used throughout.

Pupils need to know the masses of these two participating trolleys; and they should be allowed to find those by weighing. (Far better; if the loading is done by stacking trolleys, they just count trolleys—provided all trolleys have been adjusted to have the same mass.)

(B) Inelastic collision In a similar head-on collision the first trolley hits the second and sticks to it so that the two of them proceed as one unit.

(C) Multiflash photos The taking of the photograph is a demonstration. Issue a print to each pupil to analyse.

Use small ring-magnets with a cardboard or metal lid and solid carbon dioxide under the lid. The ring-magnets slide over a level glass table, and collide elastically.

Take pictures of some of the following events:

a. One ring moving on a glass table. (We hope to see constant velocity.)
b. A ring moving with constant velocity makes a head-on collision with a ring of the same mass.
c. A ring moving with constant velocity makes a head-on collision with another ring of double mass (arranged by piling an equal ring on top).

And very important collisions in two dimensions:
d. A ring moving at constant velocity makes a collision with a stationary ring and the two move off in different directions. This will need analysis of the momenta as vectors and will raise important new questions.

e. (OPTIONAL) A collision between two rings which are already moving. This is both difficult and grand, requiring careful graphical analysis. If there is time for this to be done and discussed carefully, it will be a rewarding experiment.

Vectors The last two demonstrations involve velocities, and therefore momenta, in different directions. Explain that, like velocity, momentum is a vector, that is, something to be added by geometrical construction. Teachers will need to discuss vectors and addition of vectors quite carefully at this point. But this should be very brief. If simple geometrical addition is presented as obvious, pupils will accept it. We shall need vectors even more strongly in Year 5.

For the analysis of oblique collisions, either draw a line to represent the total momentum—drawing the line in each case in the proper direction—or simplify matters by resolving the momentum into components; preferably components along the original ring's momentum and perpendicular to it.

These are experiments that a teacher will find delightful if he has had time to try them out on his own so that the techniques of taking the photographs and the tricks for the analysis are not a worry at a time when pupils are struggling with new ideas.

(D) Collisions with pendulums
(OPTIONAL) If the laboratory has facilities for hanging long pendulums from the ceiling, pupils should observe directly (or measure with multi-flash) elastic collisions between steel balls (and perhaps also some inelastic ones when the balls are made sticky with wax or Plasticine).

(E) Collisions in a row of elastic balls A set of steel balls on bifilar suspensions makes a fine demonstration. Buy a well-made one in a toyshop.

{Behind the simple story of the momentum of the impinging ball travelling through a line of balls and sending the front ball of the line forward, there is a complicated story of a propagation of a compression wave through a ball. The complete transfer of momentum from one ball to the next is even more surprising when one thinks of it in terms of compression waves.}

(F) 'Explosion' As a class experiment, pupils arrange two trolleys on a level table (not friction-compensated) and push them together until the buffer rod has compressed the spring and the catch holding the rod in is latched. When the catch is unlatched and the spring pushes them apart they will travel out in opposite directions towards markers at the ends of the table.

(G) 'Inverse explosion' Pupils hold a pair of trolleys some distance apart and attach a large rubber band or a spiral spring to pull them together. The trolleys start at rest and are released simultaneously. Pupils watch to see the motion that is left over when the trolleys have met and stuck together.

(H) Collision with marbles
(OPTIONAL) (Reports of this experiment differ greatly. Some teachers who have practised both the experiment and its teaching consider it is a very clear experiment which leads to fruitful discussion. Others report that the adjustments are tricky and the ideas of the analysis are difficult to teach—therefore they do not consider this experiment worth doing.)

This experiment uses earlier knowledge: that a marble projected horizontally takes the same time to reach the floor as a marble dropped vertically from the same height. It is therefore a good experiment in that it shows how a physicist uses one piece of knowledge in investigating the next.

A marble rolls down a ramp to hit another marble at the edge of the table. Both proceed to the floor as projectiles. Pupils mark their landing points on the floor. They deduce velocities and analyse momentum-changes in the collision.

Nuclear collisions Tell pupils that the collisions they are analysing are models of nuclear collisions which we can infer from cloud-chamber photographs. Post photographs up for all to see. *Pupils' Text 5* has some pictures.

The expansion cloud-chamber was shown first in Year 1. If pupils missed this, it should come out now, although the explanation of its action will come in Year 5. Show a cloud-chamber at work.

(I) Electrostatic forces *(OPTIONAL NOW)* Since one of our uses of collision experiments will be in interpreting cloud-chamber pictures, pupils might be shown a collision where electrostatic forces are controlling ones. However, this also comes properly in Year 5.

(J) Magnetic forces Pupils should see a demonstration of a head-on collision between toy train trucks carrying strong horseshoe magnets to give repulsive forces at close encounter.

This demonstration is important as a reminder that in collisions we do not have to have 'contact'.

THE EXPERIMENTS

The details of the suggested momentum experiments are given below. We hope teachers will make their own selection and will decide whether the experiments they choose should be done as class experiments or given as demonstrations. The later trolley experiments on kinetic energy will probably be best treated as demonstrations—unless the class is keen and has neat fingers for running the trolleys and plotting the graphs of potential energy. So one or two class experiments on momentum-conservation may be welcome here.

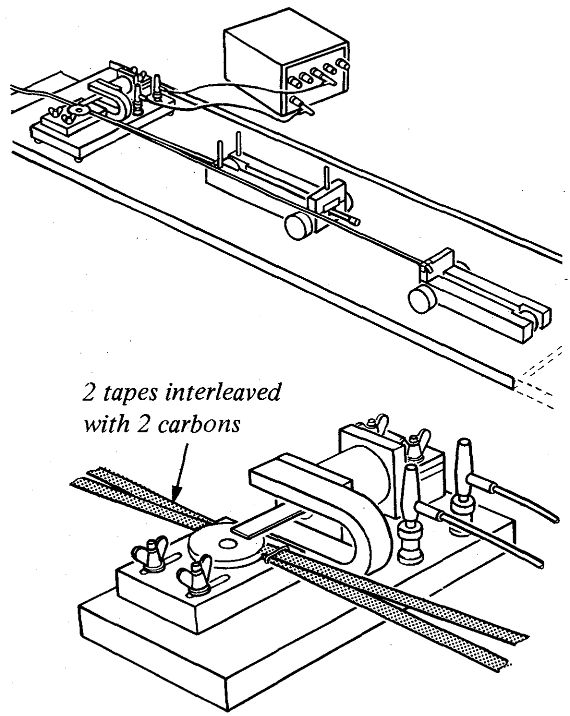
The capital letter used for each experiment in the previous list is repeated, for easy reference, at the beginning of each box.

(A) Class Expt or Demonstration 39 Elastic collision of trolleys

Apparatus

16 to 24 dynamics trolleys	item 106/1
8 to 12 runways	107
8 to 12 timers	108/1

Each group will require three trolleys, one runway and one timer (or two).



Procedure

In these experiments the colliding bodies have constant speeds before collision and constant speeds (of different size but in the same direction) after collision. Before the experiment, make it clear to pupils that they are going to measure SPEEDS, not ACCELERATIONS.

Pupils follow these instructions:

* * * * *

Set up a runway and compensate it for friction.

Place two trolleys on the runway, each with a tape attached. Run both tapes through the same vibrator with *two* carbon paper discs one for each tape. Compensate the runway for friction with both tapes running through the timer.

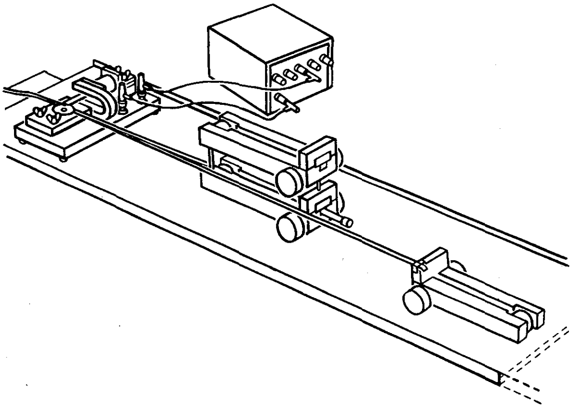
Start with one trolley at rest about half-way down the runway. It should have its spring-loaded piston out, to act as a buffer in a collision. Hold the second trolley at the beginning of the runway, give it a push with your hand, then leave it to run with constant speed until it collides with the first trolley.

Your tapes will give you records from which you can read three steady speeds:
SPEED of the moving trolley before the collision
SPEED of the moving trolley after the collision
SPEED of the other trolley after collision.

Then you can calculate the total forward momentum before and after the collision. You may take the mass of a trolley to be 1 kilogram in this experiment.

There is no need to make tape-charts. Just read the steady speed of a trolley by measuring the length of 5 tenticks on its tape. Then to calculate the trolley's MOMENTUM multiply by its MASS.

I Collision of UNEQUAL masses Give the second trolley (the 'projectile') double mass by piling another trolley on top. Watch what happens when it hits the stationary trolley.



Repeat the collision, with tapes to measure speeds.

Each partner should obtain a set of tapes for a collision.

Calculate the momentum, *mv*, of

(i) the projectile trolley, before collision.

(ii) the stationary trolley, before collision (zero).

(iii) the projectile trolley, after collision.

(iv) the stationary trolley after collision.

How does the total *mv* after collision compare with the total *mv* before?

II Collision of EQUAL masses Repeat the experiment with a single projectile trolley hitting a single stationary trolley head-on.

* * * * *

Notes

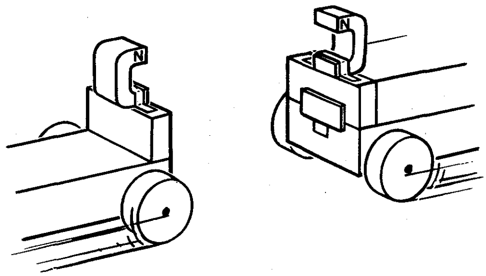
1. If the trolleys have equal masses and one has its spring buffer out so that the collision is elastic, the moving trolley is brought practically to rest and the stationary trolley picks up the full motion. Although this special case is amusing, it is better to start with *unequal* masses—otherwise velocities are confused with momenta.

2. Some teachers prefer to use two timers, one for each tape.

3. The relative masses can be varied either by piling up extra trolleys or by loading a trolley with kilogram 'weights'. But the latter method is best avoided because it leads to confusion between MASS and WEIGHT when the trolley has to be weighed.

Extensions

Two types of collision A fast group might try a 'soft' collision with a buffer and a 'hard' one without. Does the time-of-collision make any difference to conservation?



Silent collision (OPTIONAL—this requires extra magnets) Ask some pupils to attach large magnets to their trolleys and examine the momentum-changes in a completely silent collision. (The small magnets recommended for experiments with toy train wagons are *not* strong enough for this; so unless large horseshoe magnets can be obtained, this part of the experiment must be omitted.)

Pupils should try an inelastic collision to see whether momentum is conserved. They place two trolleys on a runway compensated for friction. One trolley carries a tape to make all records. The second is initially at rest and the first trolley sticks to it on collision. Then pupils can measure with their tape the initial speed of the first trolley and the later speed of the combination after collision.

(B) Class Expt or Demonstration 40 Sticky collisions: inelastic impacts

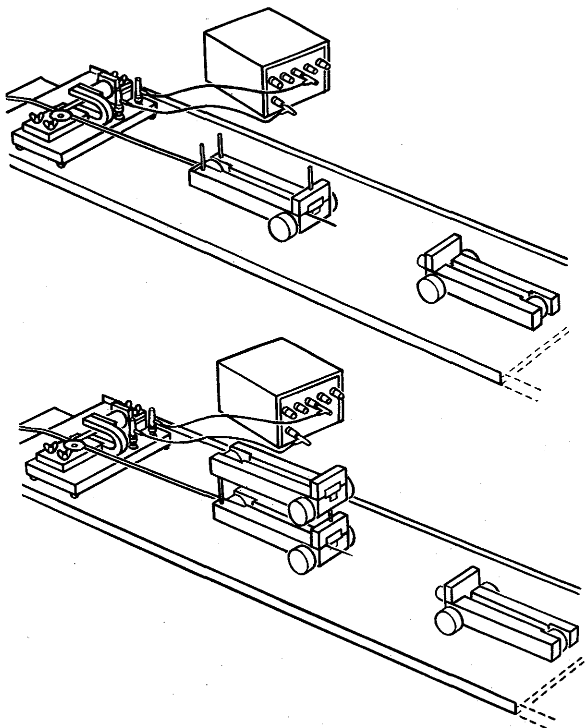
In these experiments the colliding bodies have *constant speeds* before collision and *constant speeds* (of different size, but in the same direction) after collision. Before the experiment, make it clear that pupils are to measure *speeds*, not *accelerations*.

Two trolleys are placed on a runway compensated for friction. One trolley carries a tape to make all the records. The other trolley is initially at rest and it is arranged to stick to the first trolley on collision. Then pupils can measure with their tape the initial speed of the first trolley and the speed of the combination after collision.

Apparatus

24 to 36 dynamics trolleys	item 106/1
8 to 12 runways	107
8 to 12 ticker-tape vibrators	108/1
corks	
needles or large pins	

Pupils work in groups of two or four. Each group needs two trolleys at first and later a third trolley as well. Each group needs only one timer and tape—that will give them a complete record.



Preparation

Make sure the trolleys all have approximately the same mass. Fix a needle on the front of the first trolley, and a cork on the back of the second trolley so that trolleys stick together on collision.

The collisions will be inelastic: as the trolleys stick together and move as one body. A lot of kinetic energy is lost at impact (50% in the first experiment) but we hope to find momentum conserved as always. Pupils test this hope.

Procedure

Pupils follow these instructions:

* * * * *

Let one trolley run into another on a runway and arrange for them to stick together on collision. Make tape measurements to find out what happens to momentum when the collision occurs. One trolley has a sharp pin on it and the other a soft cork to make them stick together.

You will be measuring constant speeds in this case, not acceleration—though of course, there are violent accelerations in the very short time of the collision itself.

a. Equal masses Set up a runway with a timer at one end and tilt the runway to compensate for friction with a trolley pulling the tape.

Place the other trolley without tape about halfway along the runway. Make sure it is at rest.

Start the trolley with the tape near the beginning of the runway. Give it a quick push and let go, so that it runs at constant speed. Its motion will be recorded on the tape. After the collision, the tape will show the motion of the two trolleys which are locked together.

Each member of the group should make his own tape record of that collision.

Measure your own tape and find the first trolley's initial speed, in centimetres per tentick. And measure the speed of the two trolleys after collision in centimetres per tentick.

Call the mass of one trolley M—or else just 1 kg. Calculate the total momentum before collision and total momentum after collision.

b. Unequal masses 2:1 Repeat the experiment, starting with twice as much moving material. For this, pile an extra trolley on top of the first trolley and anchor it with tape. Run a collision. Measure the tape and calculate the momentum before and after collision.

* * * * *

(C) Demonstration 41 Multiflash photos of momentum interchanges

Apparatus

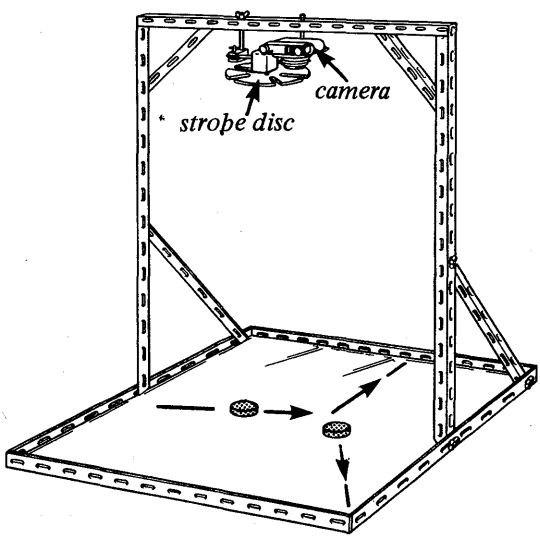
1 Edinburgh CO_2 pucks kit‡	item 95
1 CO_2 cylinder	19/1
1 dry ice attachment	19/2
1 camera	133
1 motor-driven stroboscope	134/1
1 gantry for CO_2 pucks kit ‡‡	161
cleaning materials for glass	

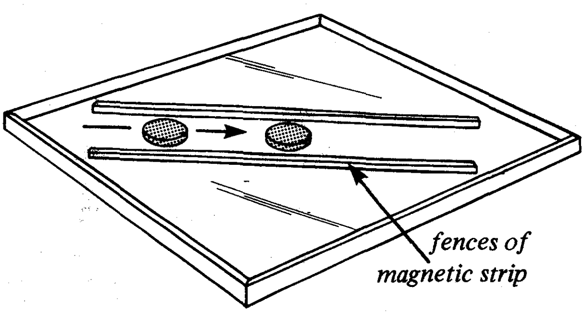
‡ If the school already has an air-table this may be used instead of the glass sheet and CO_2.

‡‡ Alternative forms: (a) A trolley runway placed across two lab stools; (b) a 45° mirror in front of the camera which faces horizontally, resting on a table near the edge.

Preparation

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





Level the plate carefully with the wedges. The CO_2 pucks themselves afford more sensitive tests of levelling than a spirit level.

Procedure

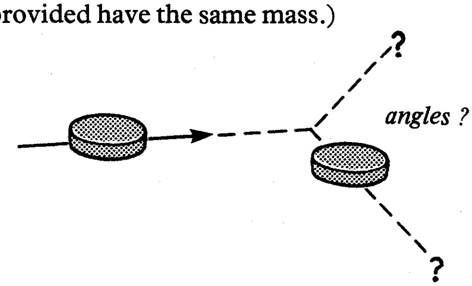
Place two or three cm^3 of solid CO_2 underneath the lid of the puck, which will float on a layer of gas as the solid CO_2 evaporates.

To avoid troublesome condensation of water on the glass plate, work with the lab window open. Do not let a puck rest in one place for long.

a. Take a multiflash photo of a single puck moving freely across the plate. The photo should show constant velocity.

b. Take a photo of a magnetic ring making a head-on collision with another ring of the same mass, originally at rest.

c. Repeat (*b*) with the second puck having twice the mass of the moving one. (Put one of the brass rings on top of the magnetic ring—all the rings provided have the same mass.)



d. Take multiflash photos when the collisions are not head-on. Let a magnetic puck moving at constant velocity make a collision with a stationary magnetic puck at such an angle that the two move off in different directions. (This important experiment will be an introduction to two-dimensional collisions. It will need the analysis of the momenta as vectors and will raise important new questions.)

e. *(OPTIONAL, for fast groups)* Take photos of collisions between two pucks which are already moving. This is more difficult but rewarding.

Notes

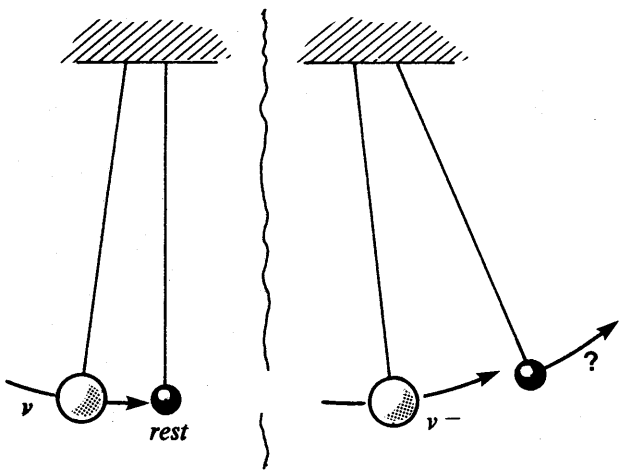
1. Take care with the magnetic pucks to avoid their being chipped as this will limit their effectiveness.
2. In photographing head-on collisions of pucks, put magnetic strips across the glass plate, in order to confine the motion to one dimension. Repulsion between the strip and the pucks keeps the pucks' motion linear.

(D) Demonstration 42 Collisions between long pendulums *(OPTIONAL)*

This demonstration requires very long pendulums. If these can easily be hung from the ceiling, these experiments should certainly be shown.

Apparatus

1 steel ball with hook ($2\frac{1}{2}$ cm diam)	item 131C
2 steel balls with hooks (5 cm diam)	131B
1 steel ball with hook ($1\frac{1}{2}$ cm diam)	131D
Plasticine	570



Procedure

Elastic collisions Show both elastic and inelastic collisions as follows:

a. Head-on collisions between two equal masses (large balls).

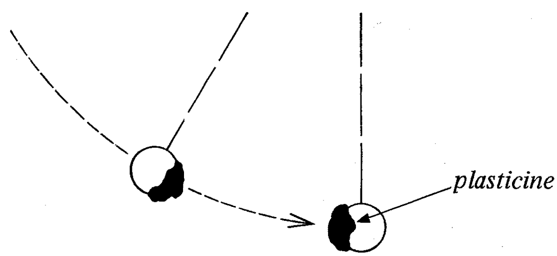
b. Head-on collisions between the medium and large masses.

c. Oblique collision between a moving mass and an equal mass at rest (large balls).

If the collision is sufficiently elastic, the angle between the two paths after collision will be 90°. We hope that some pupils will notice this. If they do, either promise that they will later on see a cloud-chamber photograph which shows this, or produce the picture at once (an alpha-particle hits helium nucleus: important nuclear information).

d. Collisions between a very small ball and a large massive one.

This is a very interesting type of collision. If the large ball is at rest, the small one will move up to it and bounce back with almost its original speed. That seems obvious enough; and pupils would predict it if asked to guess beforehand. But then reverse the pattern: ask what will happen if the large ball is moving and the small ball is at rest. Pupils will find it hard to guess. Try the experiment and show that the small ball moves on in the same direction as the large one with almost *twice the original speed* of the large one. Here again, if we have multiflash equipment ready, a picture of such a collision shows the doubling of speed clearly. This is the story of a moving massive bat hitting a light ball. See the discussion on page 93.

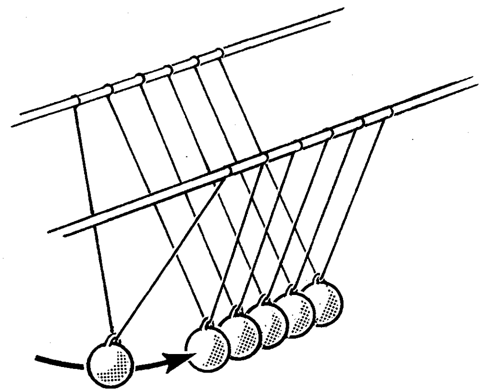


e. Inelastic collisions (OPTIONAL ADVANCED) Produce inelastic collisions by putting soft sticky wax or Plasticine on the ball at rest in such a way that the balls stick together on collision. Although such inelastic collisions are important, this particular demonstration is not one that pupils understand clearly and easily. *It should be omitted for all but a very fast group.*

(E) Demonstration 43 A line of colliding balls

Collisions of balls *rolling* along a channel are confusing because their rotational motion upsets the simple exchange of momentum in elastic collisions. It is best to avoid them.

Excellent assemblies of steel balls on bifilar suspensions are available commercially as toys. If possible buy or borrow one of these. Failing this, a similar arrangement can be constructed as suggested below.



Apparatus ‡

6 steel balls	item 131A
2 or 4 retort stands and bosses	503, 505
2 rods	504
thread (braided or monofilament fishing line is best)	239

‡ Preferably buy a good ready-made assembly.

Preparation

The apparatus consists of a line of steel balls, each hung by a bifilar suspension. Toy shops now sell well-made ones. (A home-made version takes considerable time and trouble to construct and adjust: solder or cement two small hooks to each ball; suspend each by two threads from parallel horizontal rods; adjust the suspensions so that the balls all hang in line at the same level. If any ball is displaced laterally from the rest, or is too high or too low, the demonstration fails.)

Procedure

In spite of risks to adjustment, pupils should play with the apparatus themselves. It would be tantalising to watch someone else operating what is now a well-known toy.

(F) Class Expt 44 Explosion between two trolleys

Apparatus

16 to 24 dynamics trolleys	item 106/1
8 to 12 runways	107
blocks of wood (to act as stops)	

Arrangement

Two trolleys are placed in contact. A compressed spring is suddenly unlatched in one or both. The trolleys are pushed apart; then move freely with constant speeds.

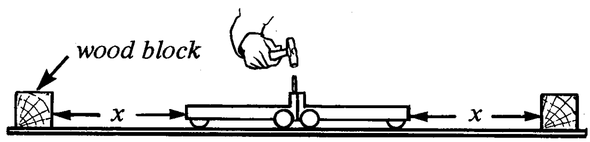
As the trolleys will move in opposite directions, it is not possible to compensate for friction. Therefore, it is not worth while to use timers and tape. Instead, pupils place blocks of wood to act as stops at measured distances from the starting points. Since this experiment deals with SPEEDS (for MOMENTA) and not ACCELERATIONS, this method of comparing DISTANCES-TRAVELLED will suffice. (In fact even the contributions to distances made by the initial accelerations are proportional to the final speeds.)

Runways are not essential for this experiment. Teachers may prefer to dispense with them and use the bench top.

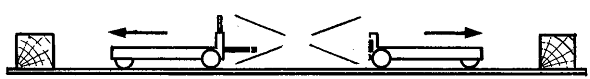
Procedure

Pupils follow these instructions:

* * * * *



x, x, equal recoil distances



Push the buffer rod in against the built-in compression spring.

You can release the buffer rod by a smart tap on the vertical release post. Then there is an 'explosion' and the trolleys fly apart.

Start with the two trolleys in contact, about half-way along the table or runway. Place a block of wood at each end of the table to act as a stop or marker.

(i) Try an explosion with trolleys of *equal masses*. Place the blocks so that each trolley moves the *same distance* after the explosion, before hitting its stop. Watch to see if your prediction of *simultaneous arrival* is fulfilled.

(ii) Explosion with unequal masses 2 :1. Repeat the experiment. Double one mass by borrowing an extra trolley and putting it on top of one trolley.

Decide for yourself how to rearrange the stops so that you expect the trolleys to hit their stops simultaneously.

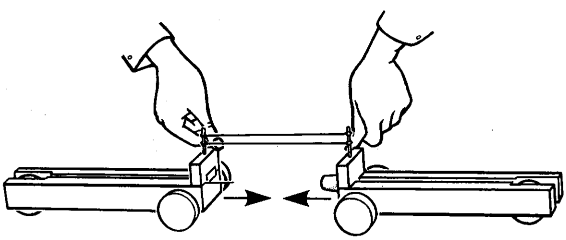
* * * * *

(G) Class Expt or Demonstration 45 'Inside-out' explosion with trolleys

This experiment should not be allowed to take much time. If there is danger of this, it should be done as a demonstration.

Apparatus

16 to 24 dynamics trolleys	item 106/1
8 to 12 runways	107
30 elastic cords	106/2
corks	
needles or large pins	



Procedure

A pupil holds a pair of trolleys some distance apart with two elastic cords stretched between them, trying to pull them together. He releases the trolleys simultaneously. The trolleys come together. The impact is made inelastic by attaching a cork to one trolley and a needle or large pin to the other so that the trolleys stick together on impact.

Pupils should watch to see what motion is left after impact.

The experiment may be repeated with one trolley made twice as massive by piling an extra one on top.

Demonstration 16 Rocket See Demonstration 16 in Chapter 2.

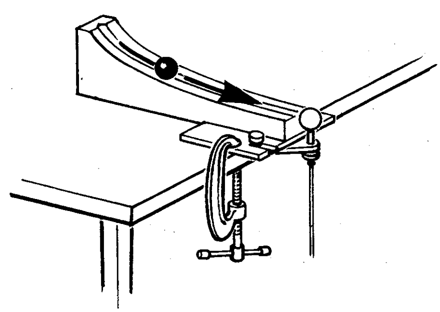
(H) Class Expt 45X Analysing a two-dimensional collision *(OPTIONAL EXTRA)*

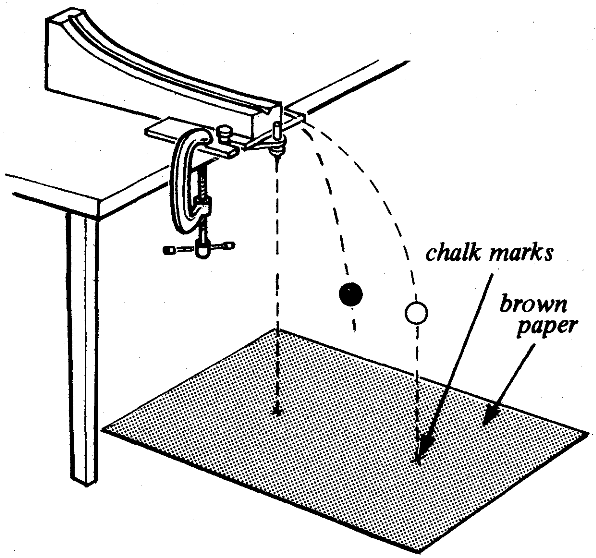
Note: This experiment takes considerable time, but in careful hands it provides an interesting study of momentum conservation. Its special virtue is that it involves good physical reasoning in the working of the experiment itself. It should be treated as an optional experiment—outside the normal scope of the programme—because of the time it takes.

Apparatus

1 kit for collisions in two dimensions	item 174
(the kit contains apparatus for 16 pairs of pupils)	
each pair also needs:	
G-clamp	44/2
large sheet of brown paper	
marbles	

The kit includes steel balls of diam. 15 mm. The marbles should have about the same diameter. The marbles used in the two-dimensional kinetic model kit (item 12) are suitable.





Procedure

Pupils clamp the ramp at the edge of a bench with a G-clamp. When they let a steel ball run down the ramp, it is projected horizontally off the end of the ramp and finally lands on the floor. Pupils place a large sheet of brown paper on the floor. They mark the point of impact of the falling ball with chalk on the paper.

Pupils use a plumb line to locate the point on the drawing paper vertically below the point of projection and they mark that on the paper. The distances between this point and the points of impact of balls are proportional to the horizontal velocities of the balls on projection.

Pupils need to understand the reasoning underlying this. This is an unusual experiment because the working of the apparatus itself involves interesting physical reasoning. Therefore, that reasoning should be brought out in discussion with pupils—it should not be given to them ready-made.

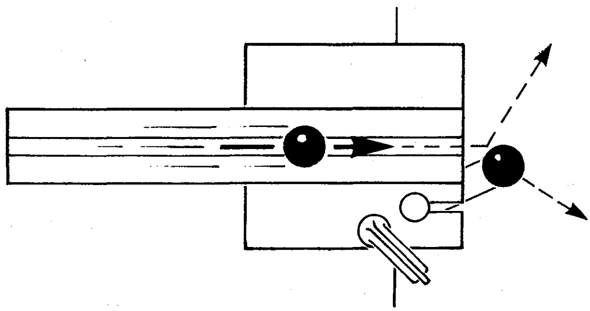
Before the experiment is done ask whether the vertical fall is dependent on the horizontal motion, and how long the vertical fall will take for one size of ball compared with another.

Head-on collision Pupils balance a marble on the support which is attached to the bottom of the ramp. They arrange this so that the ball is *exactly* opposite the end of the ramp. When the steel ball travels down the ramp, a collision occurs and both balls finally hit the paper.

Pupils find out, by calculation from their measurements, whether momentum is conserved in the collision. They need to compare the masses of the steel ball and the marble by weighing.

They estimate the velocities by measuring the horizontal distance travelled by each ball in the time of vertical fall (which is assumed to be the same for each). They must measure from the proper starting-point for each ball; the two starting-points at the collision are spaced apart by the sum of the two ball radii. If pupils do not realise this of their own accord, warn them of it.

For this part of the experiment the balls *must have different masses*. If the masses are the same, the original ball will be left with little motion after impact and it may catch the support in its fall.



Oblique collision Pupils offset the support for the ball that is hit. This time they should use balls of the *same mass*.

They allow for the radii of the balls on impact and calculate momenta. This time they must draw a vector diagram to test for momentum conservation.

For comparison with cloud-chamber photographs of alpha-particles in helium, pupils should look for the 90° angle between paths of equal masses after collision.

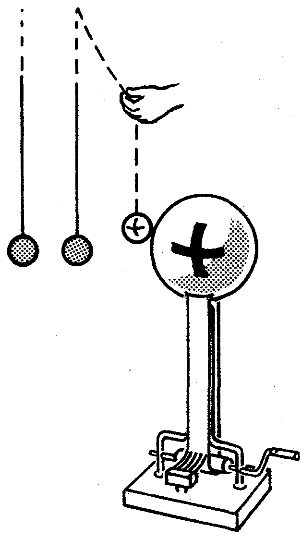
(I) Demonstration 46 Collisions controlled by electric charges *(OPTIONAL NOW)*

Apparatus

2 table tennis balls coated with Aquadag	item 131E
1 Van de Graaff generator	60/1
fine nylon thread	51E

Preparation

Coat two table tennis balls with Aquadag to make them conducting. Suspend them one diameter apart by fine nylon threads (as long as possible, preferably from the ceiling).



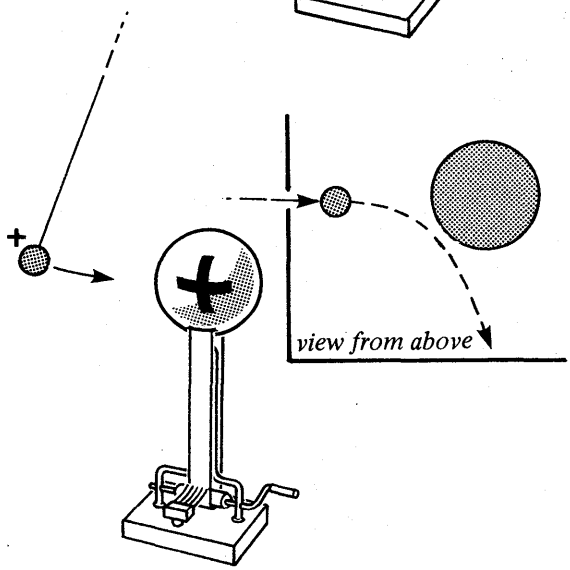
Procedure

a. Equal masses, similar charges Set the Van de Graaff generator going and let each ball touch the Van de Graaff sphere so that it becomes charged with the same sign.

Show collisions between the balls by drawing back one of the threads and allowing that ball to swing to the other.

Pupils should see the 90° angle between paths after collision; but its interpretation should be left to a later stage. Here it is only suggested as an illustration of a collision involving 'invisible forces'.

b. Orbit near a large mass Show the collision of a charged table tennis ball with the massive Van de Graaff sphere.



(This will be a useful introduction to the Year 5 work on the scattering of alpha-particles in gold foil, but at this stage little time need be spent on it and only a brief reference should be made to the alpha-particle story.)

MOMENTUM AND ATOMIC KNOWLEDGE: THE ALPHA-PARTICLE STORY

Collisions of pendulums and trolleys are fun to watch but not as strongly relevant to everyday life as one might hope. The new knowledge hardly alters young people's care in driving cars—however much we preach—but it becomes essential when we extrapolate from the range of man-sized experiments to astronomy (Year 5) and atomic physics.

Pupils who read Newton's work in astronomy will see how he used momentum in discussing Kepler's equal-areas law—though the geometrical argument is not easy.

Pupils who wish to understand the necessity of believing in atoms, must have a clear feeling for momentum.

Belief in atoms In the 19th century chemical knowledge had made atoms highly plausible, and chemistry was using an atomic hypothesis for clear exposition. Yet, before we accept the chemical evidence as completely convincing, we might reflect that the idea of an element having several isotopes would have seemed an unthinkable breach of simplicity. And in fact, at the end of the century, one or two distinguished scientists still maintained, with logic, that atoms were *not proved* to be essential or real. The facts of electrolysis had added strong persuasion, but atoms were still only a useful hypothesis. Even experiments to measure e/m failed to give convincing proof, since their results might apply to a charged stream of uniform fluid.

Historians tell us it was cloud-chamber pictures that finally dissolved the sternest critics' doubts.

Alpha-particle tracks In atomic physics, a cloud-chamber picture is the best compelling evidence for a nuclear atom:

1. For every forked track, we see many straight tracks with no fork. In each straight track, we know from counting water drops that more than a hundred thousand drops were formed. We assume that each drop formed round an ion made in the wet air. From that we infer that whatever made the tracks made a hundred thousand or so 'trivial' collisions with atoms.

We say 'trivial' in the sense that the projectile never moved off course noticeably. Therefore it must have hit things of enormously smaller mass. Each atom must be largely 'hollow' with only light particles such as electrons in its main bulk.

2. The rarity of forks in the pictures shows that *massive* targets (nuclei) are only a tiny fraction of an atom in size.

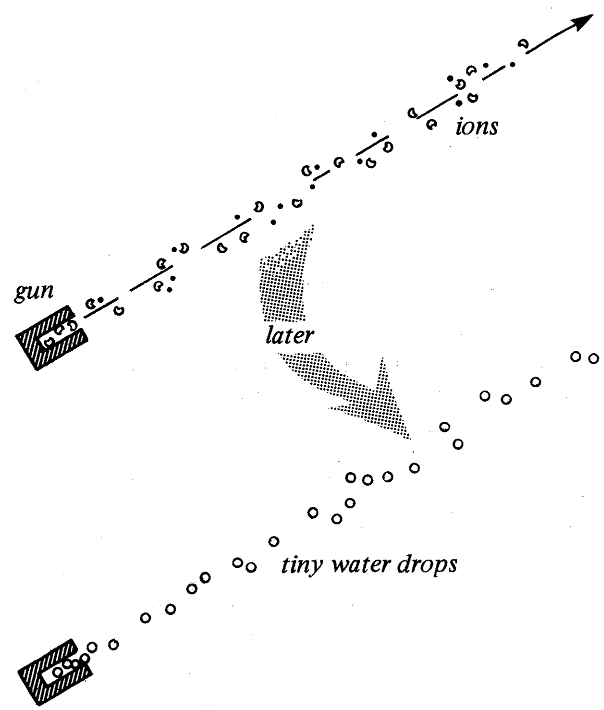
3. From measurements of forks (angles, length of tracks, and curvatures in a magnetic field) we analyse the event and calculate speeds, relative masses and energies.

All this is done with the aid of our knowledge of momentum.

Our pupils are not ready for this in Year 4—perhaps only partly so in Year 5. Yet here is the basis of our atomic picture—far better than the account the general public often gets in unsupported assertions worthy only of Galileo's predecessors.

So we consider pupils should see real alpha-particle tracks comfortably now, not in a remote demonstration but by watching an expansion cloud-chamber closely. However, we suggest postponing the detailed explanation of its working till Year 5.

Cloud-chamber pictures Pupils should have seen and used cloud-chambers in Year 1, and they will meet them again in Year 5 and use photographs of alpha-particle tracks as important



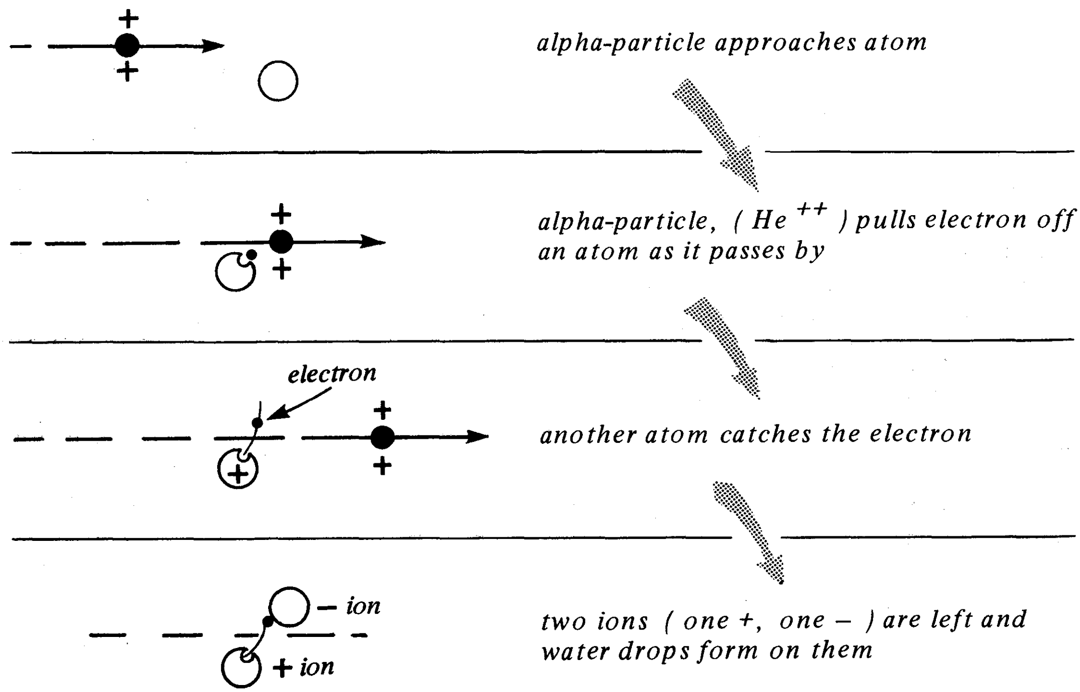
evidence for a nuclear atom model. Since we are discussing collisions now, teachers might well show some photographs of alpha-particle tracks at this stage.

Alpha-particle collisions and momentum We want to find out all we can about the masses and energies of the particles involved in such events. Whenever we attempt such an analysis of a 'fork' in a cloud-chamber photograph we assume that *momentum* is conserved in *every* such nuclear event. (We could, of course, test Conservation of Momentum if we trusted other estimates. Sometimes we can make independent estimates of momentum but usually we assume conservation.)

Alpha-particle collisions and energy We cannot carry pupils through a detailed discussion of energy changes in such events until they have met kinetic energy. However earlier teaching should have given a picture of kinetic energy as 'motion energy', and in discussing cloud-chamber pictures we are not likely to need a quantitative measure of K.E. So discussion such as the following could come now, or it could be postponed until after kinetic energy has been treated, or even until Year 5. It would be a pity not to turn our studies of momentum to this important use in discussion with pupils.

Where an alpha-particle hits some other nucleus that was effectively at rest originally, we see the tracks of two moving particles proceeding after the collision. We assume Conservation of Momentum in two dimensions. Knowing the gas that was bombarded, we can guess what the target nucleus was, and thus know the relative masses of alpha-particle and target nucleus. That enables us—assuming momentum conservation—to find the velocities before and after collision, on some arbitrary scale. Then we can find out whether kinetic energy was conserved in the collision.

If we find K.E. was *not* conserved we have a choice: either we have come across a rare but interesting case of an inelastic collision; or we guessed wrongly about the identity of the target nucleus. The latter mistake may well occur, because whatever gas is used in the cloud-chamber there is also water to make the water drops. However, a skilful reader of cloud-chamber pictures soon learns to recognise the alternative targets and can then scan a large number of pictures successfully for the very rare unusual inelastic events. The latter are nuclear transformations effected by an alpha-particle; and in those cases we do not find kinetic energy conserved—we may well find that the particles that emerged from the collision have more kinetic energy than the alpha-particle that went in.



Demonstration 48 Expansion cloud-chamber

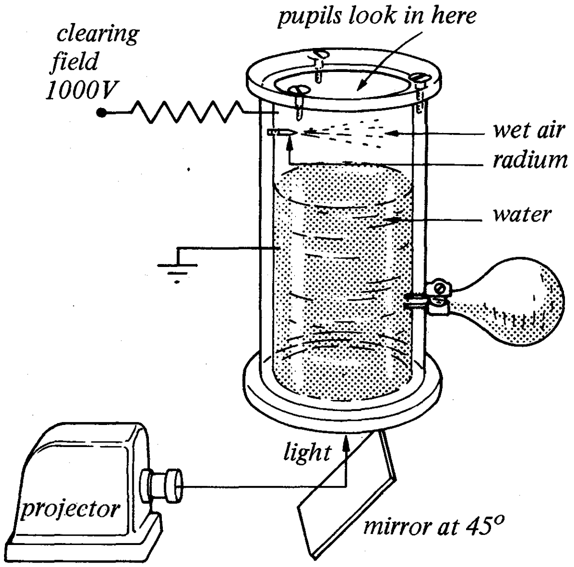
Apparatus

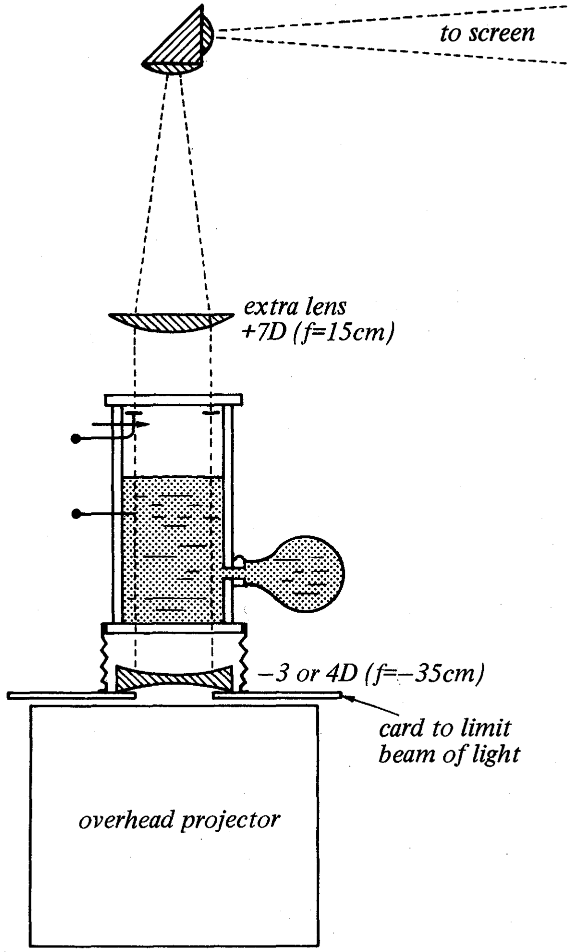
1 expansion cloud-chamber — item 18
1 E.H.T. power supply — 14

Procedure

Various types of expansion cloud-chamber are available commercially. They differ greatly in effectiveness and clarity for small groups of pupils, so we advise teachers to 'try before buying'. Much depends on the illumination. Some require special alcohol, but those which work with water are preferable.

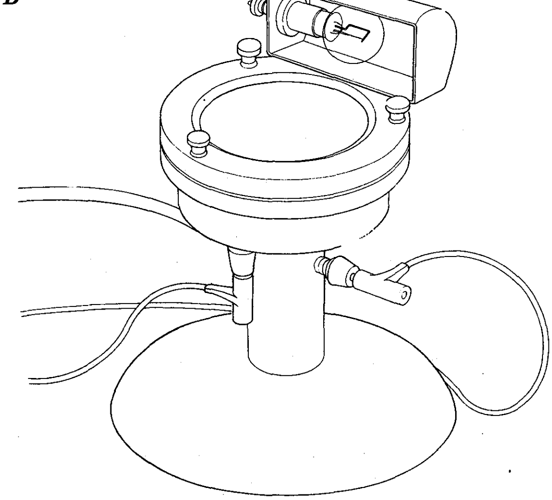
A





Sketch A shows a Princeton University design used (i) for a few pupils viewing directly; or (ii) for projecting a large image by an overhead projector.
Sketch B shows another design.

B



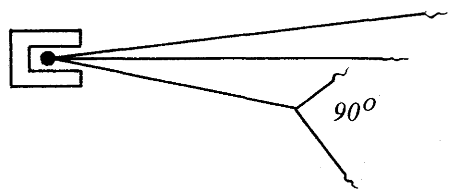
All types need an electric field to sweep away ions left by earlier events. In each case the manufacturer's instructions should be followed carefully.

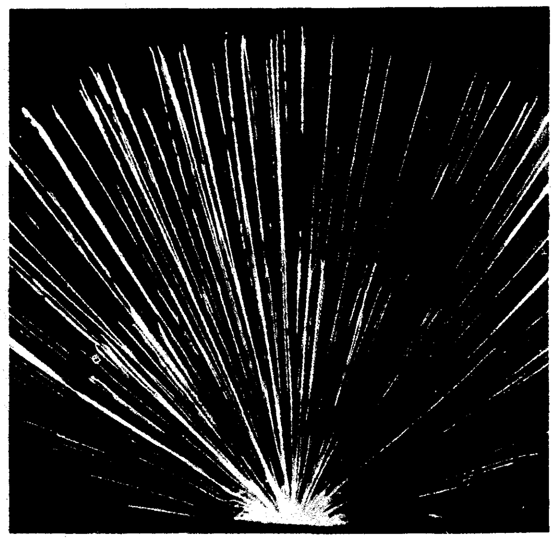
The diffusion cloud-chambers are suggested for a class experiment in Year 5.

Exhibit 47 Cloud-chamber pictures

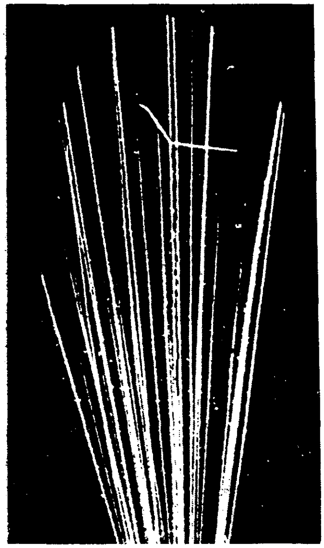
Procedure

Place a collection of cloud-chamber photographs on display. These should stay on view for some time. Include examples of forks resulting from nuclear collisions; and in particular an example of a 90° fork of an alpha-particle colliding with a helium nucleus. There are cloud-chamber pictures in *Pupils' Text 5*.

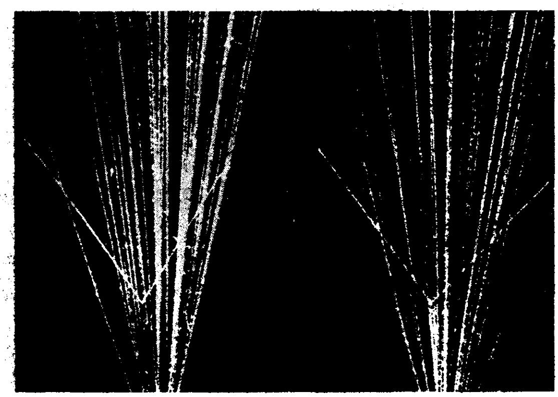




Alpha-rays from a small source: a mixture of thorium C and C′. Note there are two lots of alpha-rays, each with a definite range in air. (J. Chadwick.) From *Radioactive Substances and Their Radiations*, by Rutherford, Chadwick, and Ellis; Cambridge University Press.



Alpha-rays in wet nitrogen. One suffered severe collision with nitrogen nucleus and moved downward. The recoiling nitrogen nucleus made the short thick track. (P. M. S. Blackett.)*



Stereoscopic photos of alpha-rays in wet helium. The pictures show on analysis that the two tracks after collision make 90° with each other. (P. M. S. Blackett.)*

Alpha-rays in wet hydrogen. One suffered severe collision with hydrogen nucleus, which recoiled forward and upward, making a thinner track. (P. M. S. Blackett.)*

* From *Proceedings of the Royal Society of London*.

(J) Demonstration 49 Silent collision with magnets: head-on impact of trolleys *(OPTIONAL NOW)*

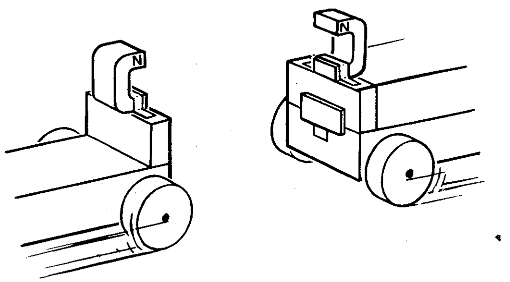
This demonstration is important as one more reminder that in collisions we do not have to have visible or audible 'contact'.

Apparatus

2 dynamics trolleys	item 106/1
2 horseshoe magnets	
Sellotape	92N

Pupils may have seen this experiment in an earlier year, with flat trucks on gauge-0 railway track. This time it may be shown again with those or with dynamics trolleys with which pupils are now familiar.

The trolleys may run on a smooth table: a runway is not necessary. If they run askew, confine them to a road between fences of wood (e.g. metre rulers) clamped to the table.



Preparation

Fix the strong alnico horseshoe magnets on the ends of the dynamics trolleys with Sellotape.

Procedure

Show collisions.

'Contact' With a fast group at this stage raise the question, 'What is contact? Is there ever real "contact" down at the microscopic level of atoms and molecules?'

In fact all that happens is that forces rise steeply to big repulsions as those particles of which matter is made move closer and closer—or so we suppose, on our present physical models.

The repulsions grow so large that even though they act for a very short time during the collision they are able to bring the colliding bodies to a stop and then push them apart again. There is always a 'distance of closest approach', which grows smaller and smaller as we make the collisions more violent when we project the colliding objects faster towards each other.

{Forces in collisions are forces exerted by one group of atoms, or molecules, on another group. We can begin to describe those forces by considering the force between two isolated molecules or atoms. We should not go into such detail with pupils now; but it is interesting to have thoughts about those forces as background for our teaching.}

ATOMIC AND MOLECULAR FORCES

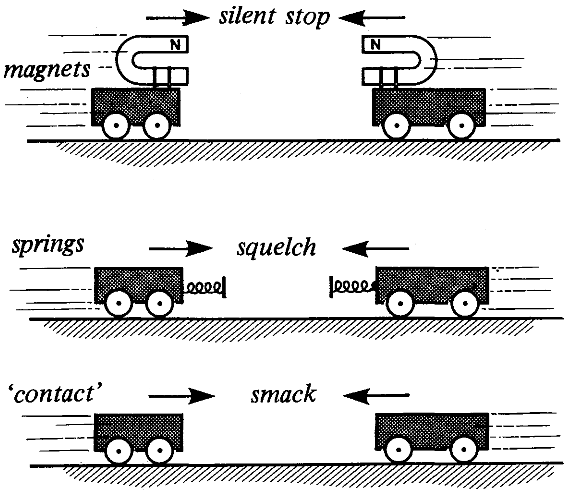
{The attractions between atoms or molecules are *short-range* forces—we know from the fact that two pieces of metal placed side by side do not attract each other noticeably.}

{The *short-range* attractions extend out only a few molecule diameters at most. We know that from invetigations 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.) The strength being independent of thickness right down to very thin films suggests that only very thin outer layers, each thinner than half the thinnest film, provide the tension. The interior region of the film contributes nothing—we argue this because we see that it does not matter how thin that middle region is.}

{Even in a gas, we may imagine 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.}

{There must also be repulsions, or solids and liquids would collapse under the attraction: but these repulsions must be very short-range forces. They cannot have the same falling-off with distance as the attractive forces—otherwise the atoms or molecules in solids would never settle down to a definite spacing as they do. Reflect that strong repulsions which only appear noticeably at very close approach, a small fraction of a diameter, are just what we imagine when we picture gas molecules colliding with each other. (For a macroscopic model, think of two billiard balls repelling as they collide.)}

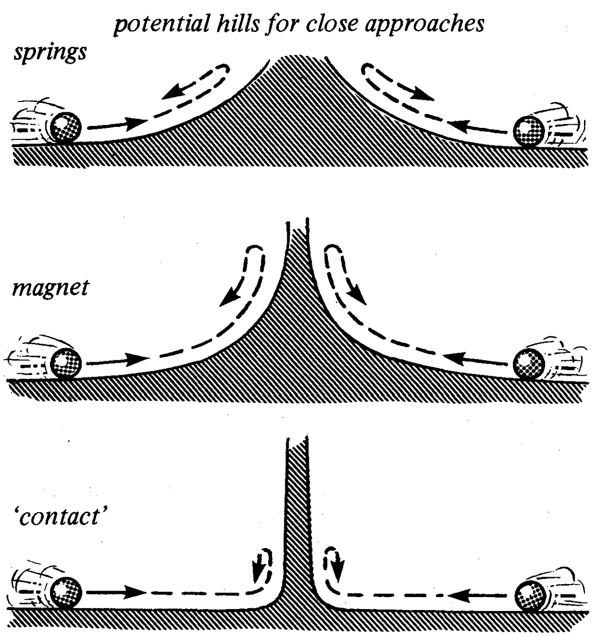
{We think of the repulsive forces as not appearing at all until one molecule goes smack against another in a collision. Of course there is no real 'smack': there is only the very sudden

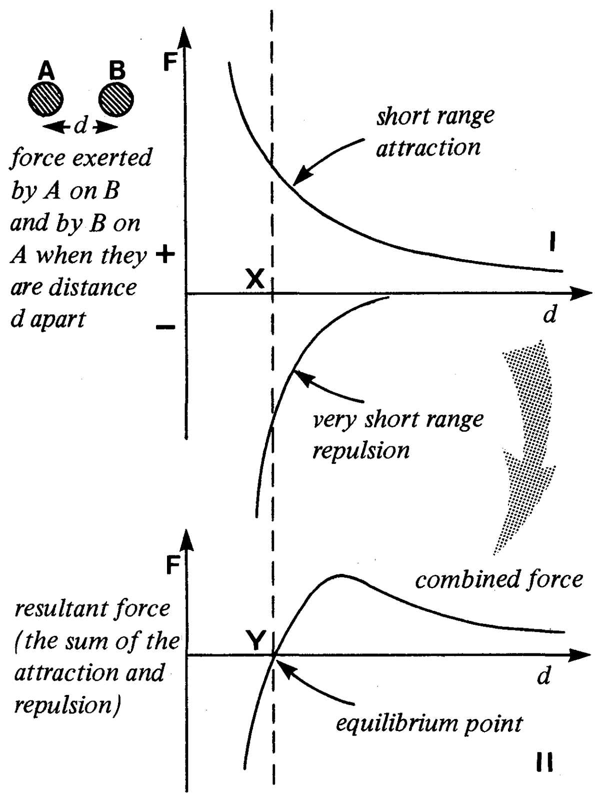


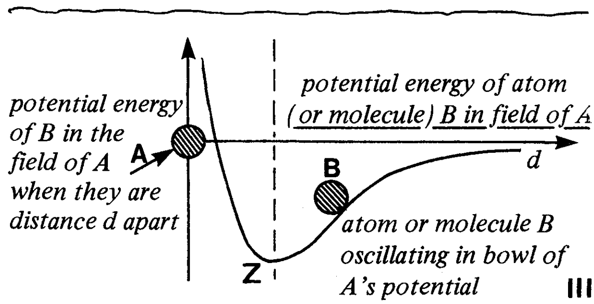
slowing-and-stopping-and-starting-away-again of the molecule in the strong force field of the other's repulsion.}

{It is the difference between attractions which grow with decreasing distance, and repulsions which grow more steeply at closer approach that provides the elastic properties which we see.}

{The sketches show: (i) a graph of the two competing types of force between a pair of molecules, plotted against distance apart, d; (ii) the combined, resultant, force, plotted against d; (iii) potential energy of one molecule in the force field, plotted against d.}







{Considering only one atom or molecule, the equilibrium position in which it should settle down in the field of a single neighbour is shown by the point X on graph (I) where the two forces just balance, or on graph II at the point Y, or at the point Z on graph III where the potential energy is a minimum. In practice, the particle does not 'settle down' but remains 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 Z. 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 than the inverse square law of electric force between isolated charges or gravitational force between 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 pupils to think out or enjoy knowing about at this stage, but it is something that we as teachers should think about.}

USES OF MOMENTUM CONSERVATION

We shall not do much for the good name of science if pupils merely arrive at Conservation of Momentum and then make no use of it. We may suggest conservation by a theoretical discussion and encourage pupils to test it by experiments; but then they must make some use of it. There are two kinds of use which could justify our teaching:

1. Pupils add this great general rule to their collection of laws or rules of nature that are either extracted from experiment or at least found to fit in with the behaviour of the natural world. If pupils make this addition without really understanding it—just one more butterfly in the box—that is not a good use. But if pupils have seen, by their own experiments, that this simple rule, 'total momentum remains constant', applies over a wide variety of events—and promises to be a universal guiding rule to describe natural behaviour, shorn of the decorations of local circumstances—then it is a worthy part of their collection of knowledge.

2. Pupils see at least one example of the Conservation of Momentum being trusted and used in a practical measurement, as follows:

Measurement of speed of bullet This is a genuine application of Conservation of Momentum. It is not difficult or dangerous; so we hope that teachers who find it unfamiliar will try it.

Pupils measure the speed of a bullet, *assuming* the Conservation of Momentum.

They also measure the speed by a time-of-flight method which does not assume Conservation of Momentum. If, as we hope, there is reasonable agreement between the two estimates we have some practical support for Conservation of Momentum as well as a demonstration of a method that put it to use.

Use an air rifle for safety, and fire a bullet into a block of Plasticine on a toy train wagon. The wagon is initially at rest on a length of track which is tilted enough to compensate for friction. The bullet embeds itself in the Plasticine sharing its momentum with the wagon. Measure the speed of the wagon (with bullet in it) by timing its motion over a short distance of track.

Pupils *assume* Conservation of Momentum and calculate the muzzle velocity.

After pupils have learnt about kinetic energy and know the expression $\frac{1}{2}mv^2$ for it, we could return to this demonstration and ask them to calculate the initial kinetic energy of the bullet and the final kinetic energy of [bullet + target] afterwards. They will find that almost all the K.E. of the bullet disappears. Ask where it has gone.

Demonstration 50 Speed of rifle bullet measured by momentum-exchange

Apparatus

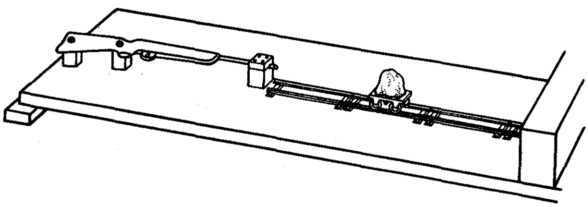
1 air rifle ‡	item 159
pellets for air rifle	159/1
5 lengths gauge-0 straight railway track	10R
1 flat truck, gauge-0	10S
1 metre rule	501
1 stopclock or stopwatch	507
300 grams of Plasticine	570
wood board	
balance (0–5 kg)	206

‡ An air *rifle* is better for the demonstration than an air *pistol*—avoid the latter and discount reports that air rifles are not available. Air rifles are manufactured and major toy stores have them.

The teacher using the air rifle for a demonstration needs a licence, obtainable at a Post Office.

Preparation

Bolt the rifle securely on its side to a board near one end. Mount it on two blocks of wood of suitable height to make sure the pellet will hit the centre of a block of Plasticine (200 to 300 grams) on the truck. The bolts go through the two blocks of wood which act as spacers. Lay the straight railway track along the board to take the flat truck with its Plasticine load. The barrel of the gun must be parallel to the track.



The assembly must permit the loading mechanism to be pulled out sideways.

There must be a safety stop for pellets at the end of the track. This may be a large block of Plasticine or clay or a large block of polystyrene with wooden backing (at least 2 cm of wood).

Incline the whole board slightly to compensate for friction, so that the truck runs down the track at constant speed when given a start.

The truck starts from rest 10 or 20 cm from the muzzle.

Place a metre rule on the board parallel to the track with its end 10 cm along the track from the end of the truck.

Procedure

Pull the loading mechanism back and then close it to cock the rifle. Insert a pellet in its holder. This holder opens when the rifle is cocked and must be pushed home once the pellet is inserted.

Fire the rifle after a count-down.

Start the stopclock when the truck reaches the beginning of the metre rule and stop it when the truck reaches the end, when the truck has travelled 1 metre. Calculate the velocity of the loaded truck.

It is tempting to place the beginning of the metre rule *at* the truck before firing, and start the stopwatch when the rifle is fired, but then pupils may associate the measurement with a measurement of acceleration from rest. We want the constant velocity of the truck (and bullet) after impact. So, for the sake of appearances let the impact occur first and then make a measurement of speed at a stage that is clearly later.

Weigh the loaded truck; and weigh a group of 10 or 20 pellets to find the average mass of a pellet.

(The following is an ingenious trick to simplify the weighing. Pellets can be bought in packets of a round number, such as 100 or 1000. Take a packet of 1000 and show pupils the label 1000. Place it on an equal-armed balance and add Plasticine to the truck to make an equal mass. Then pupils know the ratio mass of truck/mass of one pellet is 1000, and they need no other weighing.)

Pupils then calculate the velocity of the pellet *assuming* Conservation of Momentum.

In carrying out the final calculation emphasise the Conservation of Momentum, which we assume and trust here. It is helpful to use exaggerated symbols:

$$\text{Momentum before} = mV$$
$$\text{Momentum after} = Mv$$

When added to M, the tiny m of a bullet is trivial. ('Why worry about the odd needle when you are dealing with a haystack?')

$$\text{Then } mV+0 = Mv$$
$$\text{Hence calculate } V$$

Note: The rifle should be loaded immediately before firing as any delay allows air to escape and that might produce inconsistent results.

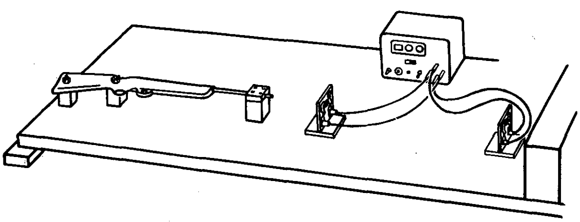
Measuring bullet speed with scaler The 'ballistic method' above is one of the methods really used for measuring bullet speeds. Nowadays, electronic devices can do the timing more easily. In fact we can show pupils a modern method for bullets. The scaler can measure a bullet's time-of-flight of a metre or so.

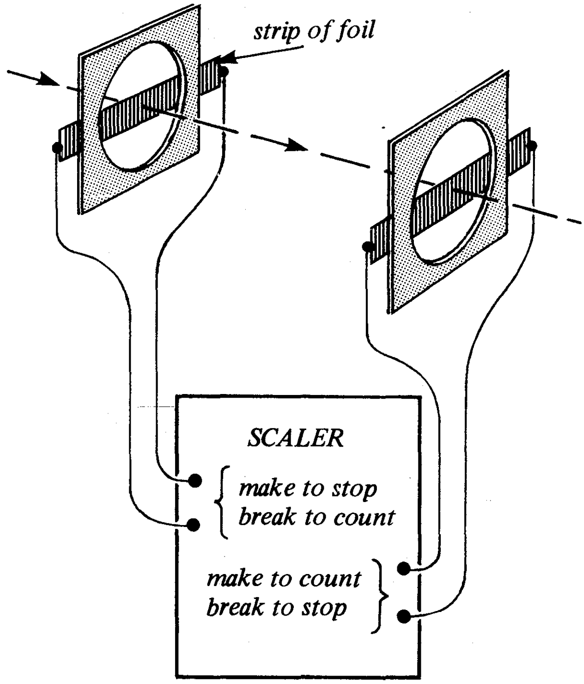
Demonstration 51 Another way to measure a bullet's speed

Apparatus

1 mounted air rifle	item 159
2 circuit breaker frames	130/1
1 scaler ‡	130/1
aluminium foil	571

‡ The scaler is used as a timing device. For details see Demonstration 12 and Appendix 4.

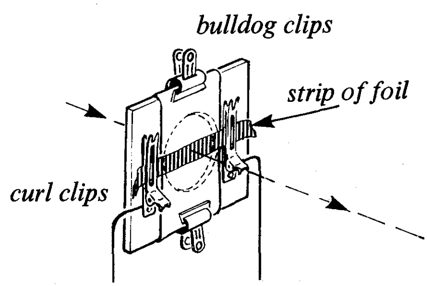




Method

Aim the rifle so that the bullet passes through two strips of thin kitchen foil, a measured distance apart, breaking each strip in turn. Connect the scaler to the strips in such a way that it starts counting milliseconds when the first strip is broken, and stops counting when the second strip is broken. Thus the scaler measures the time taken by the bullet to travel the distance between the strips.

Even with a slow pellet from an air rifle, the time to travel a metre is only a dozen or so milliseconds; so the strips should be placed as far apart as is convenient for aiming.



Preparation

Cut narrow strips of foil, 2 or 3 mm wide, 10 cm long. Set up a pair of crocodile clips, or a small wooden frame, to hold each strip. The ends of the first strip are to be connected to the 'make-to-stop' terminals of the scaler; and the ends of the second strip to the 'make-to-count' terminals.

Since the strips must be broken by the bullet, they must be set up carefully in the line of fire. Making that adjustment might waste a lot of time and spoil the demonstration by a series of misses. Therefore the metal strips should be aligned beforehand in a rehearsal, as follows. Set up a small sheet of paper at each position where there will be a strip. Clamp the rifle in position and fire a bullet through these two sheets of paper. Then install the metal strips over the bullet holes in the paper sheets. (It might be better to make the strips vertical rather than horizontal.)

Arranging stands to hold the crocodile clips and fragile strips of foil takes time and trouble. It is worth while to make two simple frames of wood or hardboard, with a hole for the bullet's path and clips to hold the strip and the rehearsal paper.

Procedure

After the rehearsal has established the line of fire and the strips have been installed, show pupils how the millisecond clock will time a bullet's flight: disconnect the first strip and then the second strip. Pupils will see that the clock runs during the time between those two breaks. Measure and record the distance between the two strips. Restore the connections and fire a bullet.

THEORETICAL DISCUSSION OF HEAD-ON COLLISION OF LARGE MASS AND SMALL ONE *(BUFFER EXTENSION)*

With a fast group of pupils show two long pendulums, one with a massive bob, one with a light bob. Let the massive bob make a head-on collision with the small bob which is initially at rest. See Demonstration 42, part (*d*).

Pupils see the small bob move ahead with almost twice the long bob's speed.

Now offer to show how that result, double speed, can be predicted by a 'theoretical' argument.

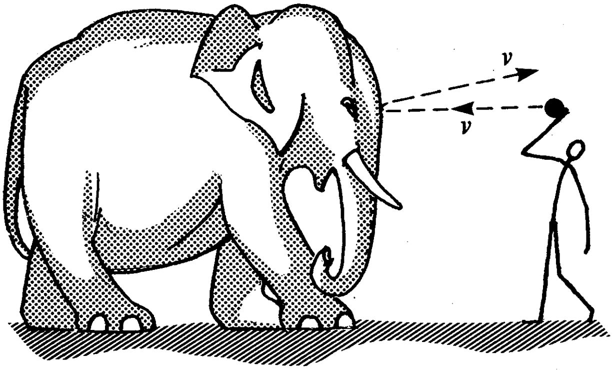
Of course we can no more predict the facts of real nature by argument than the medieval Aristotelians could; but our argument will contain a concealed piece of experimental information: a very general one that pupils accept unthinkingly—the principle of Galilean relativity.

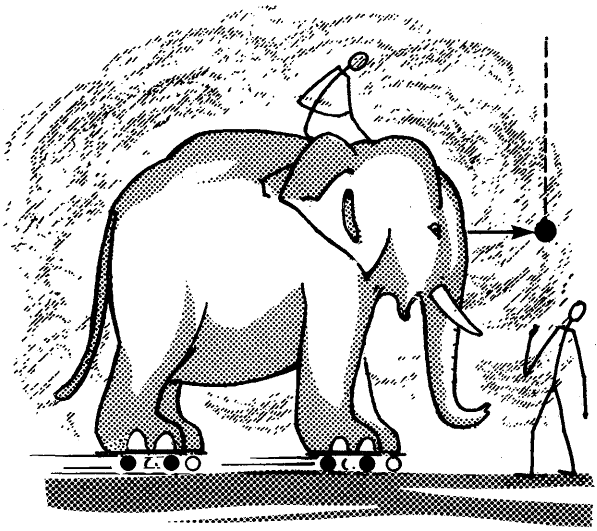
That principle says: Newton's Laws of Motion and the mechanical events that they describe are independent of uniform motion of the observer or apparatus. We observe the same laws of mechanics in a steadily moving railway train as we do in a laboratory at rest.

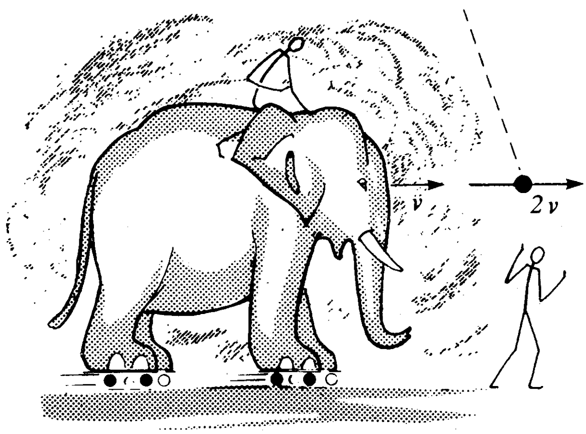
Here is the argument: Consider a collision between a table tennis ball and an elephant. First throw the ball straight at the stationary elephant's forehead at 5 metres/second. The elastic ball will bounce back with a speed almost 5 metres/second. If the elephant is on ideal roller-skates he will recoil very, very slowly, barely noticeably.

Now hang the ball at rest by an imaginary thread in mid-air and let the elephant rush towards it at 5 metres/second. When the elephant's forehead hits the ball, what motion will the ball take? It seems quite difficult to answer this until we try the following trick. Imagine the elephant surrounded by fog, so that a rider on his shoulders has no idea how fast he is moving along the road. Pretend the elephant is moving so smoothly on his roller-skates that the rider knows nothing at all about his motion. Then, in the fog, the rider sees a table tennis ball ahead. What will the rider think the ball is doing?

He will think the ball is moving towards him at 5 metres/second. He still does not know that the elephant is sliding along through the fog; and, seeing the ball rushing towards him at 5 metres/







second to hit the elephant's forehead, he knows what it will do. It will bounce away at 5 metres/second from the front of the elephant.

Now, instead, suppose there is no fog, and an observer standing on the ground, watches what is happening. The outside observer sees the ball bounce away from the elephant's forehead (at 5 metres/second *relative to the elephant*) but he also sees that the elephant himself is moving 5 metres/second. So *how fast will he see the ball move?*

We might tell pupils that this is a 'thought experiment', a useful method in theoretical physics.

This result has an interesting application in sports, and in kinetic theory of gases. Whenever a massive bat hits a stationary ball of much smaller mass, making an elastic collision, the ball moves away at double the speed of the bat. This applies roughly to the head of a golf club hitting a ball, or a tennis racquet hitting a ball when serving, or an engine shunting a light wagon.

When gas molecules hit a stationary piston head-on they rebound, on the average with equal speed in the opposite direction. But when they hit a moving piston that is *approaching* them they rebound, on the average faster in the opposite direction—they make a gain of speed which is twice the speed of the piston.

Here is new light on the heating of a gas by sudden compression. This also explains why diffusion pumps use heavy particles (atoms of mercury or molecules of oil) as their moving 'pistons'—and why those pumps are so much better at pumping hydrogen than at pumping heavy gases such as xenon.

CHAPTER 5

KINETIC ENERGY

Conservation of P.E. + K.E.

LEARNING FOR CATCHING UP

Nowadays there is more talk than ever about Energy. Discussions range widely in importance and in accuracy, and many educated people ask for fuller knowledge. This chapter contributes knowledge of one important form, kinetic energy.

Our pupils should come to understand the nature of kinetic energy and its measure. They need to know it quantitatively for application to braking cars, swinging pendulums, speeding bullets; for its relevance in the molecular theory of gas pressure; and for measurement of e/m of electrons. As well as all these they need to know it for building a general understanding of energy and its conservation.

The teaching of energy plays a very important part in our programme and the continuing development in this year depends on earlier foundations. The treatment suggested for Years 1 and 2 of Nuffield Physics (or Nuffield Combined Science) forms a necessary basis for Chapters 5 and 9 this year.

Some pupils in a Year 4 class may have missed that introductory treatment. They will need some special teaching of energy-changes and WORK. This was offered in an extra chapter for catching-up in *Pupils' Text 3*; and we offer similar treatment again here* and in *Pupils' Text 4*. It is marked † to show that it is only suggested for pupils who missed the preparation, and not as a rather discouraging 'revision' for others, who will do better to remember the earlier ideas as they proceed with the new developments.

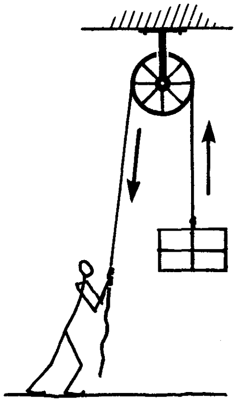
Energy-changes and work The earlier treatment started with descriptions of sources of energy, then forms and interchanges; and it made a quantitative beginning in measurements of energy-transfer. In particular, our meaning and use of WORK was explained. Pupils made experiments and did calculations. Present pupils who missed all that need some introduction. Otherwise they would find this chapter's sudden plunge into measurements of kinetic energy very puzzling. If they have met a different view of work in some other science teaching (for example as a name for potential energy) they would be confused now unless given a careful discussion of our view.

† **Review** Here—and also in *Pupils' Text 4*—there is a short review of the ground covered and views suggested in earlier years.

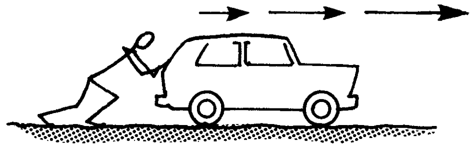
† **Energy, jobs, fuel** We started by saying that energy is something we get from 'fuels' (such as coal, oil, food and, over all, sunshine), whose change to other forms provides for 'useful jobs' such as hauling up a load to the top of a building, speeding up a car or a bullet to higher speed—and presently we include heating up a house or bath water.

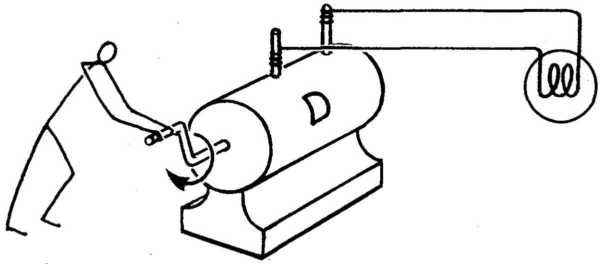
Useful jobs were described in earlier years as those jobs that need fuel, jobs that cannot be done without fuel. Though that looks like talking in a circle, it provides an adequate criterion: they are jobs that man can only get done at a cost, by drawing on his food supply or using an electric supply from a power station or using some engine run by fuel, etc.

* In addition, teachers will find notes on 'Conservation of Energy', 'Perpetual Motion and Perpetual Movement' in the General Introduction issued with *Teachers' Guide* Year 3.



Useful jobs that need fuel

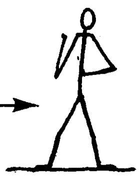




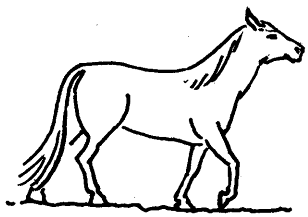
Useful jobs *are* jobs for which we have to pay money to provide the fuel or food. (True, sunshine brings us free fuel sometimes, but we have only to examine our *needs* for fuel on a cloudy day to find whether we are dealing with a fuel-needing job or not.)

Engines that need

fuel

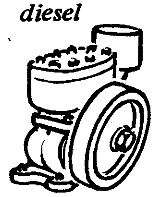


food

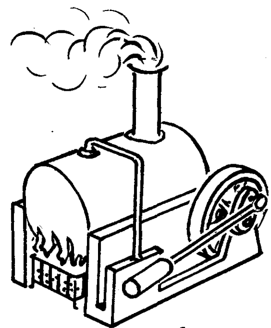


hay and oats

diesel



crude oil

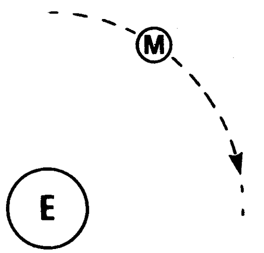


coal

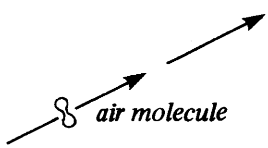
Useful jobs *are not* jobs of maintaining a big force at rest: that could be done by a bookshelf or stationary paperweight or by a tightened G-clamp.

We then dealt with the amount of fuel demanded by a job. Take the simple job of raising a load of 3 kilograms by 2 metres. Imagine that job broken up into six separate jobs, each of raising 1 kilogram 1 metre. It is safe to assert that the fuel demands for each of these 'unit jobs' are all the same, because we can picture a man doing the whole job by using a cord and pulley and standing on the ground to pull down one metre of cord with the same pull for each unit job. He pulls hand over hand, with his back straight, so that each unit job costs him the same amount of 'food energy'. Calculating on that basis, we see that we can use FORCE × DISTANCE to measure the total job.

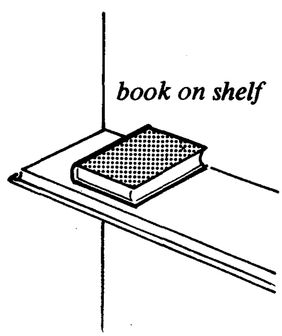
Jobs that do not need fuel



Moon's orbiting



air molecule



book on shelf

That 'job' involves an energy transfer, *FROM* chemical energy (food) *TO* potential energy. We measure the job by FORCE × DISTANCE which we name WORK.

We do not say that the work we calculate belongs to either chemical energy or potential alone. It simply tells us the amount of energy *transferred*. It tells us the energy lost by our muscles; and it tells us the energy gained by the raised load.

Thus, in this programme, work is neither positive nor negative. We say neither WORK DONE ON nor WORK DONE BY but always speak of an ENERGY-TRANSFER *FROM* one form (or place) *TO* another.

† **Energy forms** Meanwhile, we built up an informal feeling for *energy* by describing various forms, always with an underlying, but hitherto unspoken, assumption that energy is something universally conserved, something changed to another form or moved from one place to another but never manufactured or destroyed.

† **P.E. and K.E.** We described the energy given to a wound-up clock spring or a stretched spiral spring as *potential energy* or *strain energy* stored in the material of the spring. (We called that *springs-energy* at first for simplicity.)

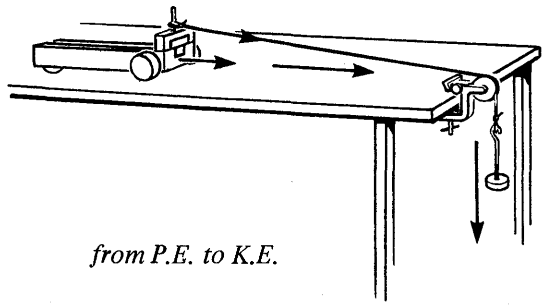
We described the energy gained by a load that we raise higher up as *gravitational potential energy*, probably stored in the gravitational field. (We called that *uphill energy* at first, for simplicity.)

Pupils could see that when we have given the spring or the load some extra potential energy it could do a useful job for us by hauling up some other load as it loses that potential energy. Or, in losing some of that potential energy, it could make some object move faster. And, in return, an object that is moving can provide potential energy by winding up a spring or raising up a load, providing it is allowed to lose some of its motion in doing so. Thus we built up a qualitative idea of *motion energy* which we later named *kinetic energy*.

Demonstration 52 Illustrations

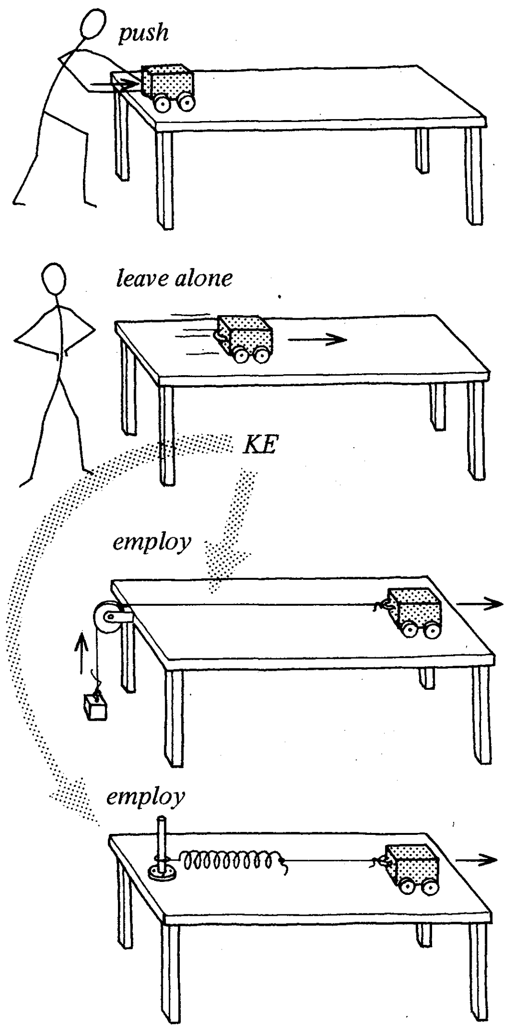
Repeat some illustrations:

(i) a small load hung on a thread pulls a trolley along, increasing the trolley's *motion energy* at the expense of the *potential energy* lost by the load;



from P.E. to K.E.

(ii) a moving trolley gives up its *motion energy* and comes to rest while raising a load or compressing a spring. (At this stage, one should carefully avoid quantitative account-keeping over the exchange between K.E. of a trolley and P.E. of a pulling load, because there are losses at the inelastic impact each time a pulling thread is jerked taut.)



† A list of energy forms We described the following forms of energy (some of them with informal names in earlier years).

STRAIN ENERGY the potential energy stored in a stretched spring, wound-up spring, bent beam, etc. (springs-energy)

GRAVITATIONAL POTENTIAL ENERGY, which is increased when a load is raised (up-hill energy)

KINETIC ENERGY (motion energy)

CHEMICAL ENERGY, stored in fuels and food, involved in chemical reactions. (This might be called molecular energy, or even atomic energy, reserving *'nuclear'* for the energy released in radioactive changes.)

MOLECULAR ENERGY In addition to the strain energy of a bent spring, etc., we must imagine energy stored in inter-molecular or inter-atomic fields, energy which changes when melting or evaporation occurs. Until we have studied heat and linked it fully with other forms of energy, we cannot say very much about this; but we should point clearly to the extra energy that steam has in comparison with water at the same temperature.

ELECTRICAL ENERGY (mentioned without clear description)

RADIATION ENERGY (which pupils met in the 'radiation circus' of class experiments in Year 2—see Year 1 and 2 *Teachers' Guide* for the knowledge that pupils should bring from those experiments. No clear description of the nature of radiation was given then; it was sometimes just called *light energy*)

NUCLEAR ENERGY (mentioned in Year 1 when a cloud-chamber and a simple spark-counter were shown. Little or no explanation).

† Heat and Conservation of Energy We also *mentioned* the idea of taking heat (measured by MASS-OF-WATER multiplied by TEMPERATURE-RISE) as a probable form of energy. We certainly made it clear that, when some kinetic energy disappears, unaccounted for by a gain of P.E., we notice that heat appears. In Year 3 we talked qualitatively of the kinetic energy of gas molecules and the suggestion may have arisen that the heat-content of a gas is related to such energy. But at no time so far have we faced the Conservation of Energy fully and openly. Yet we have had to talk as if energy were something that does not get lost, that does not appear from nowhere, yet can be changed to other forms.

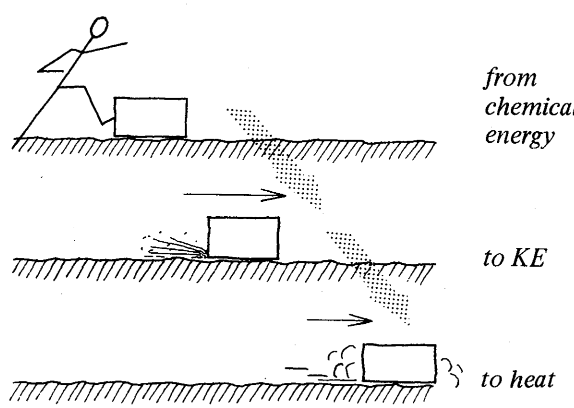
We are only now approaching a full discussion, both of the many forms of energy with their interchanges, and of the account-keeping which leads us to believe in universal Conservation of Energy.

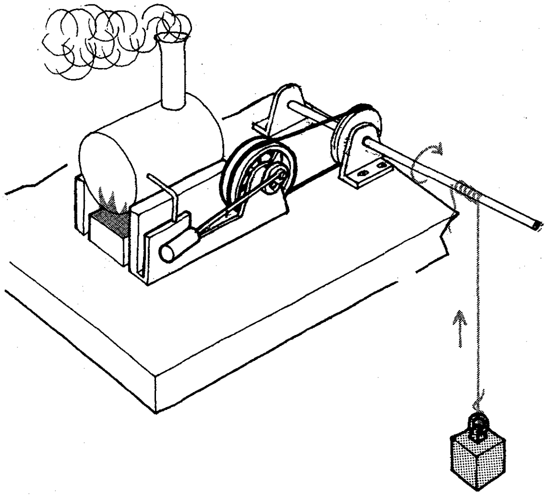
† Transfers of energy from form to form or place to place We discussed in Years 1 and 2 many kinds of energy-transfer, showing experiments and describing examples of transfers like the following.

1. A boy kicks a large box along the floor. The box comes to rest. (*FROM* chemical energy of muscles *TO* kinetic energy *TO* heat)
2. A toy steam engine driven by a Bunsen burner raises a load on a string. (*FROM* chemical energy of gas + oxygen *TO* heat in flame *TO* heat and molecular energy in steam *TO* gravitational potential energy).

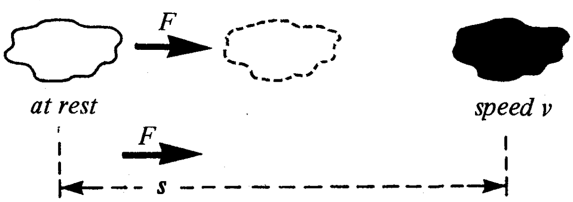
In describing each change we avoided any wording which would give the impression that energy is ever created or destroyed. We insisted on saying, for example, that energy is *transferred* '*FROM* chemical energy in the boy's muscles *TO* energy-of-motion of the box'.

We pointed out that it is not *creation* of energy that benefits mankind, but the *transfer* of it to some other form. It is helpful to transfer energy from muscles to the P.E. of a load of bricks raised to the top of a building, because we need to have the bricks up there. It is helpful to transfer the chemical energy of some coal and oxygen to heat in some bath water because we want a hot bath and cannot make the water warm just by wishing.





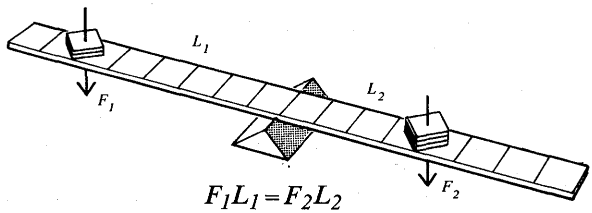
† Work as a measure of energy-transfer (see the Note on 'Work' in the *General Introduction*) In all those cases where transfer of energy from one form to another (or just from one place to another as with a see-saw) involves a force pushing through a distance, we can estimate the transfer. The product FORCE × DISTANCE tells us the amount of ENERGY transferred. It often indicates the amount of fuel that we need to draw upon that energy-transfer. So the product FORCE × DISTANCE is a very useful one as a measure of energy-transfer. Therefore we give it a name, WORK. That is a return to the old-fashioned use of the word 'work' for energy-transfer. In our programme, we suggest that WORK should be used with that meaning throughout. Teachers will find it makes the discussion of energy changes clearer.



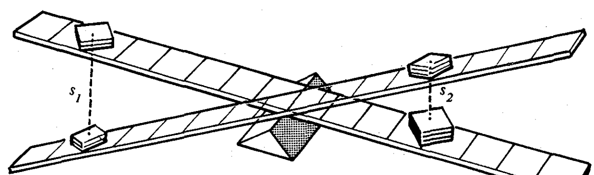
† Units for work and energy Since WORK, measured in newton · metres measures the ENERGY-TRANSFER, the same units must apply to measures of ENERGY itself.

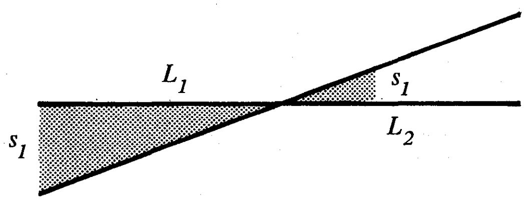
† Machines At an early stage pupils did an open experiment with a simple 'see-saw' to look for a lever law; but we did not suggest extracting a formal rule of moments. Later, when work and energy were discussed we looked at the energy-changes involved when a balanced see-saw is tilted. Using FORCE × DISTANCE or WORK as a measure of energy-transfer, we compared the input-transfer to the see-saw, as one end moved down with the output-transfer as the other end moved up.

SEE – SAW (Year 1)



$$F_1L_1 = F_2L_2$$





$$\frac{L_1}{L_2} = \frac{s_1}{s_2};$$

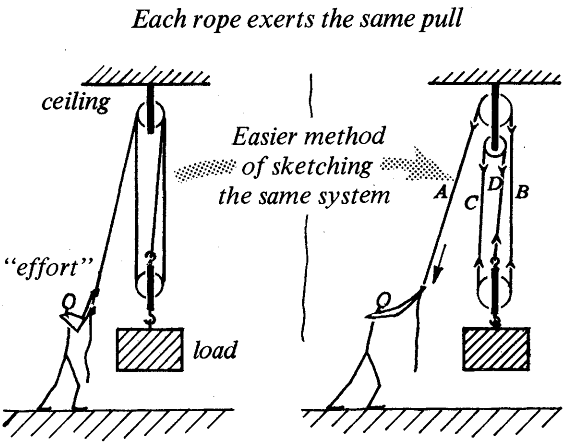
$$\therefore \frac{F_2}{F_1} = \frac{L_1}{L_2} = \frac{s_1}{s_2}$$

$$\therefore F_1 \times s_1 = F_2 \times s_2$$

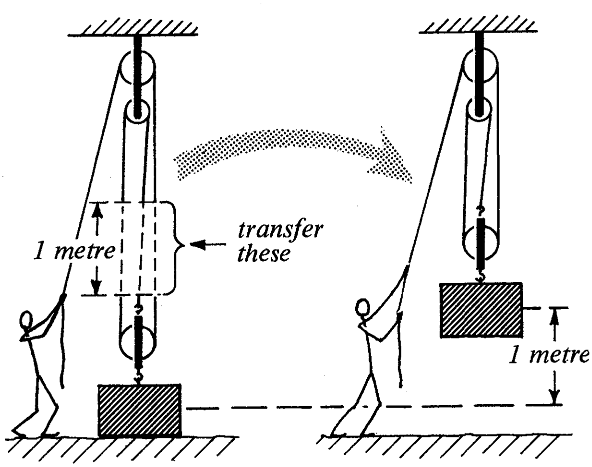
WORK = WORK

We mentioned the practical fact that a little less energy appears at the output than goes in at the input: but we left unanswered the question of the fate of the missing energy.

Pupils experimented with a simple set of pulleys with an ideal mechanical advantage of 3 to 1. Looking at the ideal force-ratio and at the distances moved by 'effort' and 'load', we found that here again the ideal output energy-transfer is just equal to the input energy-transfer.



Pulley system: Force ratio



Pulley system: Distance ratio

We pointed to a general rule: 'machines' do not manufacture energy. They do appear to lose a little energy between input and output and pupils may themselves suggest that the difference goes into heat through some mechanism of friction.

(†) **Power** Pupils may have made some estimates of RATE-OF-TRANSFER OF ENERGY in earlier years and may have met the name POWER. But this is the time for a clearer knowledge of the concept and new measurements—in Chapter 10 of this year.

KINETIC ENERGY

We now start our Year 4 teaching of energy. We remind pupils that energy belonging to motion is something very important, which we need to know more about for moving rockets, moving gas molecules and lots of other moving things. We named that energy informally *motion energy* in Years 1 and 2. Now, we should use its professional name *kinetic energy*, K.E.

We are going to treat *kinetic energy* as a measurable quantity. We shall arrive at an expression for calculating it, and there will be experiments. But the theoretical argument and practical measurements will not prove easy at this stage unless pupils have a clear qualitative picture of kinetic energy and a good feeling for it from the start.

So we suggest teachers should begin with simple qualitative demonstrations. These should be shown quickly without any attempt to measure or calculate. Pupils may repeat some of them as class experiments before the measurements, but demonstrations seem best now for a clear introduction.*

In each case we follow our practice of describing the energy change as a transfer *FROM* . . . such and such a form *TO* . . . another form.

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* We ourselves are so familiar with the concept of interchanges between kinetic energy and potential energy that we think of the experiments described here as obvious; and we should be satisfied with thought experiments: imagining men pushing a car to get it going; weights accelerating things; a spring buffer bringing a moving thing to rest. But these are not so obvious to pupils who are learning about energy. Although we could persuade pupils to imagine these changes, it is better to show them.

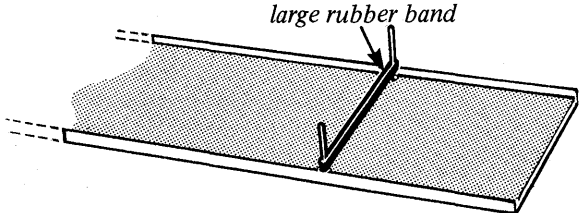
Demonstration 53 Kinetic energy: qualitative demonstrations

Apparatus

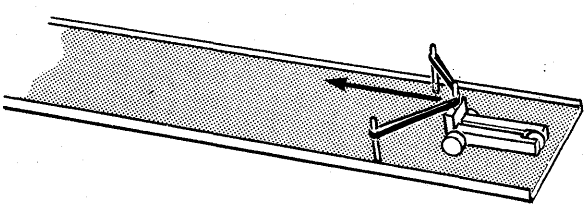
1 dynamics trolley	item 106/1
1 runway	107
1 pulley on clamp	40
1 100-gram hanger	31/2
1 expendable spring	2A
2 horseshoe magnets	
rubber bands	233
dowel rods ‡	565

‡ *Adaptation of runway* This experiment and later ones, will need a catapult stretched across the runway. This could be done by setting a massive retort stand on each side of the runway and stretching elastic between them. However, that would require too many stands when the apparatus is used for class experiments. Also it may shift.

The simplest arrangement is to drill two holes, one near each side in the base of the runway to take 15-cm lengths of wood dowel (9 or 10 mm diam.). A rubber band (e.g. 15 cm perimeter × 3 mm wide) stretched between dowels forms a good catapult.

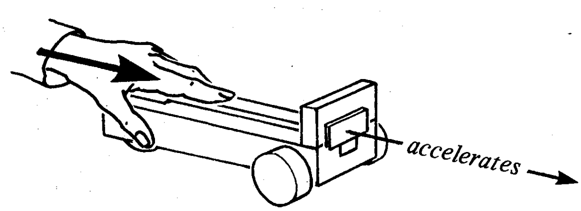


catapult



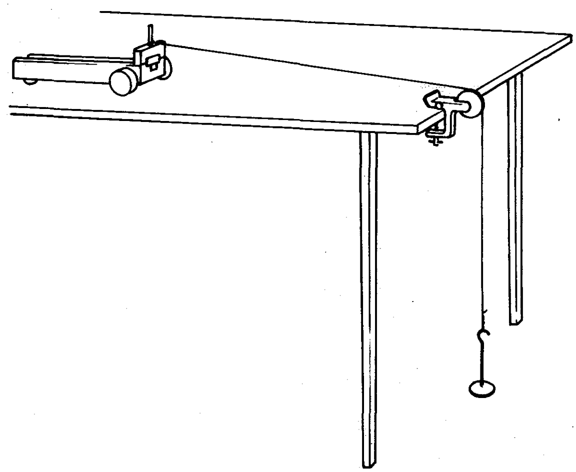
Procedure

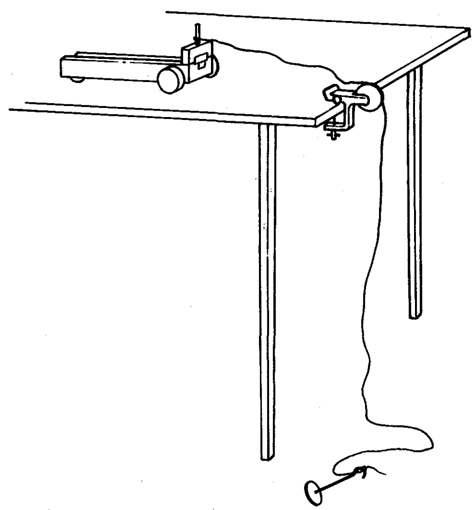
a. *FROM* chemical (food) energy *TO* K.E. Put a trolley on the bench and give it a push.



from chemical (food) energy to K.E.

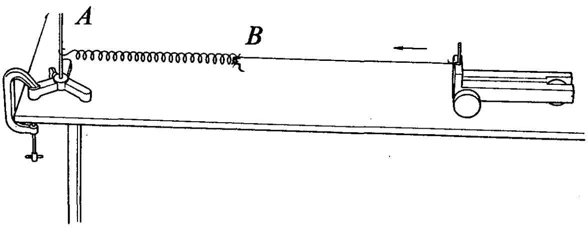
b. *(i) FROM* gravitational P.E. *TO* K.E. Put a trolley on the bench. Fasten the pulley to the edge of the bench and run a thread over it from the trolley to a 100-gram load. Release the trolley so that the load falls a short distance to the floor; then the thread falls slack, allowing the trolley to continue.





b. *(ii) FROM K.E. TO P.E.* Repeat the demonstration, but in reverse. Start the trolley moving with a push away from the pulley and let it pull the thread taut and lift the load as it comes to rest.

c. *FROM strain energy TO K.E.* Pre-stretch a spring (e.g. one from Year 1 Elastic Materials Kit) until it is clearly an open weak spring. Anchor one end (A) to the bench by slipping the end loop over the rod of a retort stand which is itself clamped to the bench.

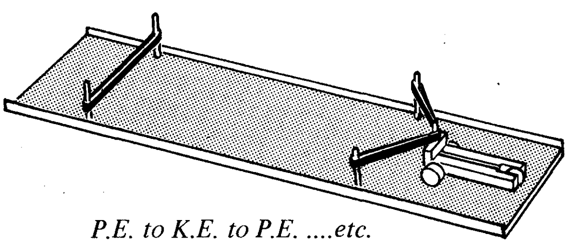


Fasten $1\frac{1}{2}$ metres of thread to the other end (B) of the spring. Then stretch the spring gently by at least 10 cm. Anchor this end (B) temporarily (perhaps in a pupil's hand). Straighten out the thread and attach the free end to a trolley. Place the trolley so that the thread is taut and then release the end (B).

Repeat the experiment, but in reverse. Give the trolley a push so that it causes the spring to stretch.

d. *FROM strain energy TO kinetic energy and TO strain energy again.*

Stretch a catapult across each end of the runway, about 40 cm from the ends.

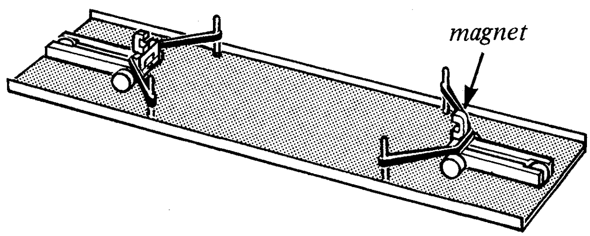


Fix a single vertical dowel rod firmly on the trolley and adjust the height of the catapult so that this vertical rod will catch the middle of it. (It is probably better to let the rubber band engage the rod, though some teachers prefer to place the catapult lower and let it engage the body of the trolley.)

Place the trolley on the runway. Pull it back by hand against one catapult so that the rubber is stretched. Then release the trolley so that it is projected by the catapult, runs along the runway and strikes the second catapult.

Expts 53e and f use special magnets, so they must remain demonstrations unless a few pupils have spare time.

e. *Collision with magnets* Attach two strong horseshoe magnets firmly to two trolleys (Sellotape will suffice). Arrange the magnets so that the trolleys will be repelled as they approach one another.



Place each trolley at an end of the runway so that they engage the catapults. Pull the trolleys back by equal amounts and release them so that they run towards one another, are brought to rest and pushed away again by the magnets before returning to the catapults. During the collision, when the trolleys are momentarily at rest, the kinetic energy they had has disappeared and is stored as some form of 'potential energy'.

(It may be necessary to rehearse this rather difficult experiment carefully to make sure that the trolleys do not slew round as they approach one another.)

f. *Exchange of energy with magnets* Leave one of the trolleys, with magnet attached, in the middle of the runway. Draw the other trolley back against a catapult. Release the trolley so that it collides with the stationary one, which moves away to collide with the second catapult.

Class Expt 54 Qualitative experiments on kinetic energy *(OPTIONAL)*

Apparatus

Each pair or quartet of pupils who does these will need:

1 dynamics trolley	item 106/1
1 runway	107
1 pulley on clamp ‡	40
100-gram hanger	31/2
expendable springs	2A
dowel rods	565
rubber bands	233

‡ Or, better, run nylon fishing line over a glass rod or tube.

Procedure

Pupils carry out the experiments of Demonstration 53a,b,c for themselves. If time permits, a fast group should try Expt 53d.

Special use in Year 5 All of these, 53a,b,c as well as 53d, e, f would make excellent *pupil demonstrations for revision* in Year 5, for pupils who would like to practise showing and describing chains of energy-changes.

CALCULATING KINETIC ENERGY

We can start a body moving from rest or just make it move faster, at the expense of chemical energy from fuel or some other supply. We need to calculate the energy-transfer to kinetic energy in such cases. And we would like to know how much energy we could get back from a moving body into some other form by bringing it to rest.

Thus we suppose that a moving body has a store of energy 'because of its motion'. And we calculate the amount of that energy with the help of Newton's Second Law of Motion. By combining $F = ma$ (or Ft = change of mv) with our use of work or [FORCE] × [DISTANCE] as a measure of energy-transfer, we find that kinetic energy is given by $\frac{1}{2}mv^2$.

Is K.E. real? In discussing kinetic energy with pupils we should not throw any doubt on its reality. Yet we should remember that our estimate of a body's kinetic energy does change when we change our own frame of reference. If we stand at rest and look at a moving body, we credit it with a certain amount of K.E.; but a moving observer credits the moving body with a different amount of K.E. If he is moving along beside the body with the same velocity, he considers the body has no K.E. Only in the case of the mixed random motion of gas molecules (heat) do we find that such a change of observers makes no difference to our calculation of the thermal energy.

* Pupils who have forgotten our use of FORCE × DISTANCE or have not met energy-teaching with work in this form, may confuse it with the momentum-changes.

Point out to pupils the contrast: instead of change of momentum which is given by *force × time*, we are now going to deal with something different, that is given by *force × distance*.

FINDING A FORMULA FOR KINETIC ENERGY
ALGEBRAIC METHOD

We imagine a force pushing an object along, making it move faster. That force must be the *RESULTANT* (or net) force on the body. We use that as the force F in $F = ma$. To find the expression for kinetic energy we calculate the work, FORCE × DISTANCE,* which tells us the energy-transfer to kinetic energy. See *Pupils' Text*.

RECOMMENDED ALTERNATIVE: GEOMETRICAL METHOD

However, the algebraic proof may seem too long to pupils to make sense. Also it appears to refer only to acceleration by a constant force, which is unfortunate when we want to treat kinetic energy as a very important quantity that is *independent of the particular way in which the moving body acquires its motion.*

Therefore we urge teachers to try the geometrical method. It is a derivation that is much easier to show with blackboard and talk than to explain in print—unless one is allowed to use calculus notation for small quantities. We can *talk* about 'a little bit of distance travelled ahead' or 'this little bit of extra momentum' but, *in print*, that looks clumsy to us and may be discouraging to pupils. However, in this *Guide*, we want to convey the general idea of the method quickly; so we shall use calculus notation, δt and $\delta(mv)$, on the understanding *that there is no suggestion whatever of giving the explanation to pupils with that notation.* It is only used as shorthand in the present communication with teachers.

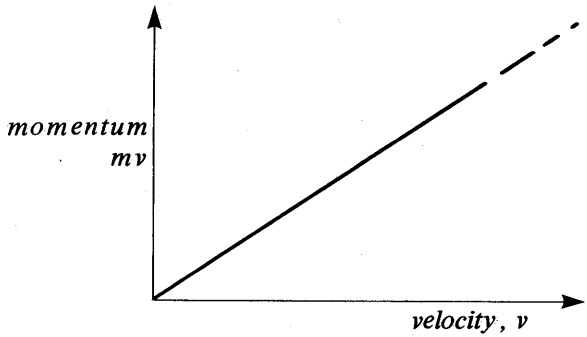
Suppose a moving object is already moving with some speed v and we are pushing on it with a (resultant) force F. Suppose the force pushes the object ahead a short distance δs. Then the work which tells us the transfer of energy *FROM* our muscles (or whatever else is pushing) *TO* the moving object is FORCE × DISTANCE, or $F\,\delta s$ in that brief exchange. That is the increase of kinetic energy in that short time. If we know the speed v at that stage of the growing motion, and the short time taken for it, δt, we can say: distance $\delta s = \text{speed} \times \text{time} = v\ \delta t$. The work that shows the increase of kinetic energy $F\,\delta s$ is $F\,v\,\delta t$. But we already know what $F\,\delta t$ is. It is:

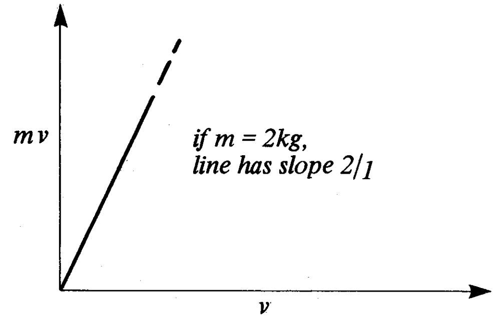
FORCE × TIME FOR WHICH THE FORCE ACTS
so it is the object's GAIN OF MOMENTUM
∴ increase of kinetic energy

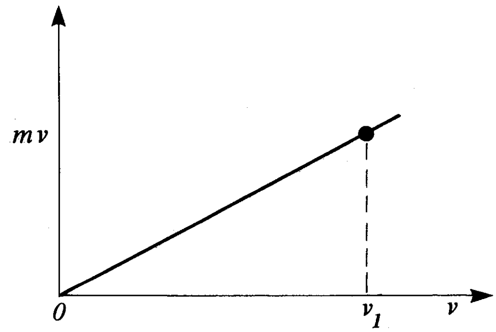
$$= F\,\delta s$$
$$= F(v\,\delta t) = (F\,\delta t)\,v$$
$$= (\text{INCREASE OF MOMENTUM})\,v$$
$$= \delta(mv)\,v$$

Note: The part above is the difficult part of the story. It may be better to postpone it until after the strange graph described below has been sketched and discussed.

Draw on the blackboard a strange graph, showing v plotted along and mv plotted upwards. Ask pupils what shape that graph line must have.*

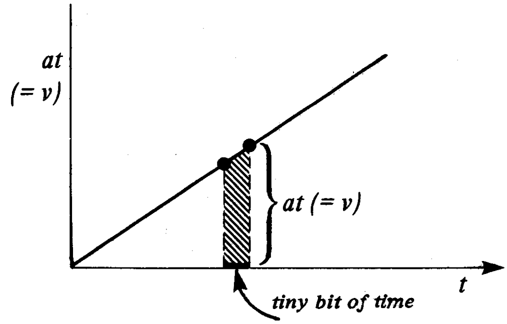






* This is an unfamiliar kind of graph. Pupils who think of a graph as a way of showing experimental results may object and say that this is not an experimental graph but only a geometrical game of drawing a line which is *necessarily* a slanting straight line. When they realise that our argument will still give us the same answer for kinetic energy, $\frac{1}{2}mv^2$, even if the point on that line which shows a particular velocity and momentum moves up and down the line with quite irregular motion—i.e. if the velocity changes in a quite irregular way—they may feel still more uneasy. To comfort them, we may offer two examples:
1. Offer to show that the area of a circle is πr^2. This is likely to be amusing and worth seeing, provided pupils already know the definition of π in the form 'circumference of circle $= \pi \times$ diameter'. Many a pupil just learns $C = 2\pi r$, and $A = \pi r^2$ without knowing whether they are connected; so we must start by explaining the basic meaning of π. See *Pupils' Text*.
2. We show them how we can derive $s = \frac{1}{2}at^2$ by drawing a graph of t along and at up. This applies *only* to constant acceleration, because with a constant, the graph is a straight line through the origin. This is, of course, a simple case of the 'Galileo's geometry' method which we used before to arrive at $s = ut + \frac{1}{2}at^2$; but in this case we are labelling the graph differently, so that its co-ordinates have the same odd property of being necessarily proportional (provided a is constant).

A strip of width δt and height at has area $at \,.\, \delta t$, which is $v\delta t$, and that gives the distance travelled, δs. Then the *whole* distance, s, is given by the area $\frac{1}{2}at \,.\, t$.



Give pupils plenty of time to think about it. To accomplished mathematicians the answer is obvious, although even they may be surprised when they ask themselves what kind of motion this graph applies to—it applies to *any* motion, however irregular.

The shape is not obvious to beginners, and needs careful introduction, by plotting point after point:

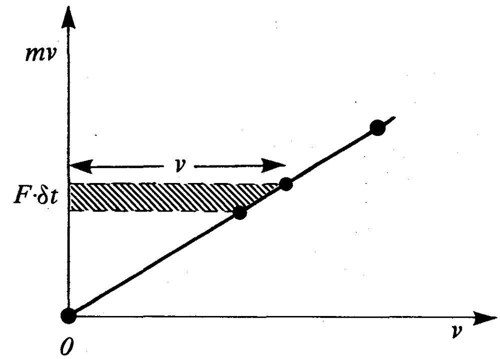
> Here is one speed that the object might have; and we multiply that by m (which might be 2 kilograms) and plot m times that speed, upwards. Here is another speed which the object might have and we multiply that by the same m (still 2 kilograms) and plot that mv upwards; and so on.

Pupils see that the graph *MUST* be a slanting straight line running through the origin.

Move a pencil or piece of chalk up the line to show how it would be plotted by various kinds of motion. For motion with constant speed, the only visible part of the line is a single point for the right velocity. For uniform acceleration from rest the characteristic point moves steadily up the line from the origin to the final speed. For the motion of a pendulum bob, the characteristic point swings up and down the slanting line, with simple harmonic motion, between extreme points corresponding to $+v_{max}$ and $-v_{max}$, that motion being 90° out of phase with the bob's motion.

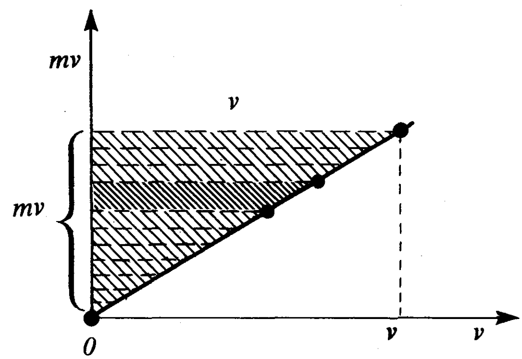
(We need not give that latter example; but we should somehow make it clear that the characteristic point can move in lots of different ways. And yet if it starts at the origin and ends at a particular speed v_1 the kinetic energy that the object then has gained is, as we are now going to see, $\frac{1}{2}mv_1{}^2$.)

When pupils understand the behaviour of this strange graph, we take two points on the slanting line quite close together and draw horizontal lines across to the vertical axis of momentum mv. Mark the corresponding two points on that vertical axis and ask what the distance between them shows. Pupils will say that it shows the small gain of momentum $\delta(mv)$. Shade that horizontal pillar. Ask what its area represents.



$$\begin{aligned}\text{Area of strip} &= v \times (\text{gain of } mv)\\ &= v \times (F \times \text{short bit of time})\\ &= F \times (v \times \text{short bit of time})\\ &= F \times (\text{short bit of } s)\\ &= \text{bit of WORK.}\end{aligned}$$

Then if some object starts from rest and ends at any particular velocity v its total kinetic energy is the total of all the transfers shown by the little bits of work, and is therefore the area of a certain triangle on the graph. That triangle is half of a rectangle of area $mv \cdot v$. Therefore kinetic energy $= \frac{1}{2}mv^2$ when velocity is v.



Seen for the first time, this seems an abstruse method; but we trust teachers will experiment with it. It is quite general—a secret evasion of calculus.

{**Extension to relativistic energy** At A-Level this might be extended to an interesting commentary on mass in special relativity. Suppose we make the following assumptions:

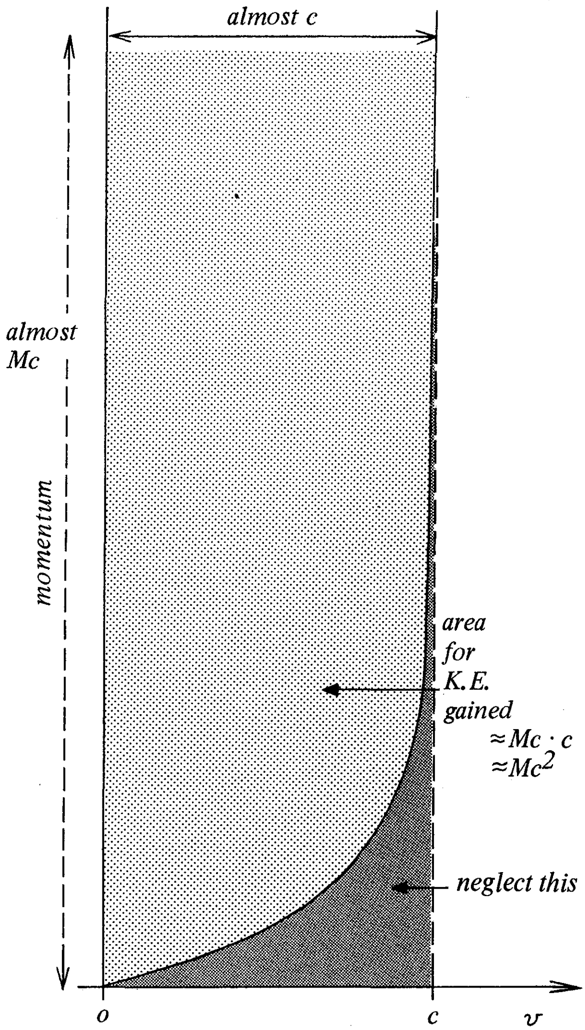
1. FORCE × TIME = change of (mv), as in ordinary Newtonian dynamics but m may not be constant.

2. As suggested by some experiments on high-speed charged particles, m does in fact increase with increasing speed—not noticeably at the ordinary speeds but markedly at the higher

speeds that we can give to electrons or charged atomic particles. To a stationary observer mass piles up to higher and higher values as the moving body approaches the speed of light. Assume that mass approaches an infinite value as the speed approaches c. (If so, we see at once that we have no hope of accelerating any material body to the actual speed of light by any finite force.)

3. Calculate kinetic energy as before, by adding up all the pieces of work $F\,\delta s$ from rest to the speed in question. It will be given as before by an area to the left of the line on our strange graph.}

{Now plot the same graph of mv against v but *extend it to much greater speeds*. Run along the horizontal axis from rest to the speed of light, c, as a practical limit. Continue the vertical axis from the origin up to an enormous value of mv when the mass has increased greatly as the speed approaches the speed of light. The graph-line is a straight slanting line from the origin at first, but presently it curves up more and more steeply until it is asymptotic to the vertical line given by velocity c.}



{As before look at the area to the left of the graph to obtain the expression for K.E. At low speeds we obtain $\frac{1}{2}mv^2$. However, if we go up to some high speed, v_1, close to c the speed of light, the mass has grown to M and the area becomes a tall strip of height Mv_1 or almost Mc. And it is a rectangle of width v_1 or almost c, except for a small 'triangular' piece at the bottom—which for present purposes we may neglect if we have proceeded to high enough energies. Therefore, as an approximation for *very* high energies, we have a total kinetic energy $Mc \times c$, or Mc^2.}

{This is not the proper relativistic expression for kinetic energy. We should subtract m_0c^2, the rest energy of the mass. The piece to be subtracted is actually given by the 'triangular' area that we neglected, but there is no easy way to show that.}

Use of $\frac{1}{2}mv^2$ Having shown that kinetic energy is $\frac{1}{2}mv^2$, we should make some use of the expression. Pupils should first look at the interchanges between K.E. and P.E. and see whether the formula fits. And they should try some problems in which the expression can be used.

KINETIC ENERGY: QUANTITATIVE EXPERIMENTS

(Teachers will find that these seem unexpectedly strange and difficult to many pupils.)

Measurements of K.E. With ticker-timer and tape to measure v exchanges can be measured between $\frac{1}{2}mv^2$ and P.E. of a falling load or a strained catapult.

Pupils calculate the potential energy lost by a falling load which pulls a trolley and compare it with kinetic energy gained by the trolley.

After that they could make measurements of exchanges with catapults and trolleys; but they have already done a lot of work with trolleys. So we suggest that teachers should save time by giving demonstrations. Of course, if pupils are keen to try the tests themselves they should do so. Or some pupils may like to repeat one of the tests in the *pupils' demonstrations for revision* in Year 5.

Class Expt 55 Measurements with P.E. changing to K.E.

Apparatus

8 to 10 dynamics trolleys	item 106/1
8 to 10 pulleys on clamp	40
8 to 10 runways	107
8 to 10 timers and tape	108/1,3
hangers with slotted 100-gram loads	31/2
1 domestic balance (5 kg)	20
nylon fishing line	239

Note: The falling load gives kinetic energy to the trolley, but it also gains some kinetic energy itself. Allowing for the latter energy would spoil the clear story at this introductory stage; so it should be neglected. Therefore, the mass of the pulling load should be only a small fraction of the mass of the trolley.

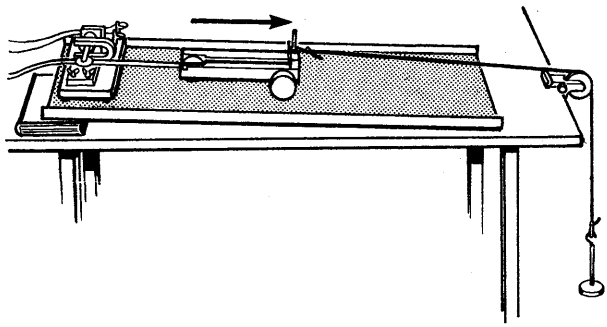
Procedure

Pupils follow these instructions:

* * * * *

Compensate the runway for friction. The friction compensation must be arranged with the ticker-tape in use, otherwise the drag by the tape may be comparable with the pull of the small load.

Fasten a pulley to the edge of the table at the end of the runway; and run a thread over it from the trolley to a 100-gram load.



Attach tape to the other end of the trolley. Pass the tape through a vibrator.

Release the trolley. The falling weight accelerates it until it hits the ground. After that the thread is slack and the trolley moves with a constant *velocity*, v. Estimate the value of v from the tape. Measure the mass of the trolley in kilograms by weighing on a balance.

Calculate $\frac{1}{2}mv^2$. Compare this with the potential energy lost by the falling load.

* * * * *

Class Expt 56 K.E. to P.E. Reverse of Expt 55 *(OPTIONAL BUFFER EXPERIMENT)*

Pupils follow these instructions:

* * * * *

Compensate the trolley board for motion in the opposite direction and use the trolley to *raise* a load.

Arrange the trolley, thread and load as before; but start the experiment with the trolley near the edge of the table, with the thread slack and some of it lying on the floor. Since the thread is slack, a pulley cannot be used, but a nylon fishing line running over a glass rod (or tube) does well. The tape runs out behind the trolley and passes through the vibrator.

Give the trolley a push, with the vibrator switched on. The trolley travels down the compensated runway with constant velocity until half way along; then the thread goes taut and the load is raised a distance d as the trolley comes to rest. Measure d.

Calculate the K.E. lost and the P.E. gained, and compare them.

* * * * *

Note: This experiment could be extended into a series of readings for different loads, different distances of fall, to provide different values of v in $\frac{1}{2}mv^2$; and the mass of the trolley, m, could be changed. Then interesting graphs could be plotted to show relationships between d and v^2, and graphs for different masses. However, *such extensions would miss the point.* They would make the experiment much longer than it deserves at this time, without making the nature of kinetic energy much clearer, and without increasing pupils' trust in $\frac{1}{2}mv^2$. Such extensions are not advised.

Demonstration or Class Expt 57 Energy measurements with a catapult and a trolley: strain energy to K.E.

Apparatus

1 dynamics trolley	item 106/1
1 runway	107
1 timer ‡	108/1
rubber bands	233
1 newton spring balance	81

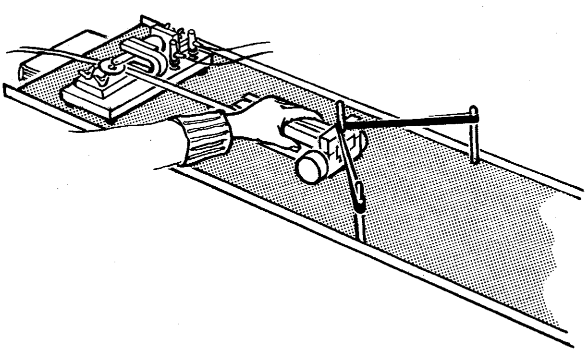
‡ A stopwatch and metre rule may replace the tape and timer.

Procedure

Warn pupils that this experiment is difficult. They must be content with rough agreement at best.

Compensate the runway for friction (including friction of the tape).

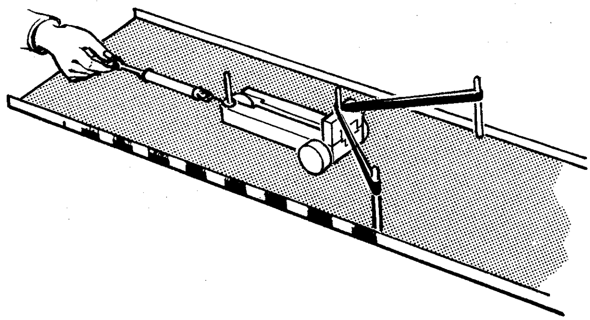
Near the upper end, set up a catapult. This is a rubber band (stretched a little) between two vertical rods. Place the rubber band at such a height that it will push on the vertical rod of the trolley. Pull the trolley back so that it stretches the rubber band. Then energy is stored in the catapult.



When the trolley is released the rubber band hurls it along the runway. Take the tape record to measure the trolley's constant speed after the rubber band has finished driving it. Show this so that pupils see what happens. The strain energy (springs-energy) stored in the rubber band is changed to kinetic energy (motion energy) of the trolley.

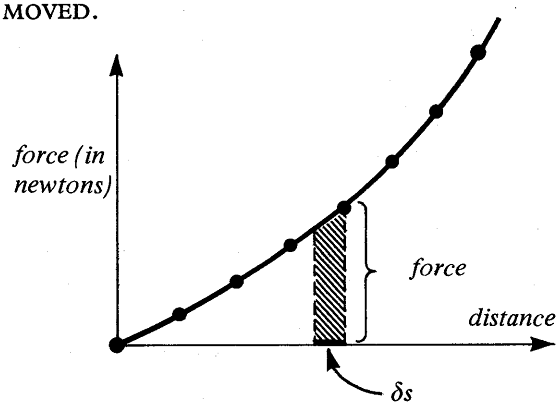
Make careful measurements of energy as follows:

(i) Measuring the strain energy stored in the catapult We must measure the WORK which tells us the energy put into storage in the catapult. That WORK is FORCE × DISTANCE measured as we drag the catapult back. *But the force is not constant:* it changes as the rubber band is stretched more and more. So we must measure the WORK bit by bit as we load the catapult.

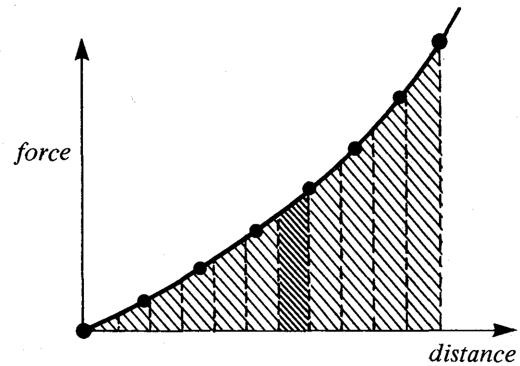


Pull the trolley back with a spring balance marked in newtons and note the reading every centimetre. At each reading of the spring balance also record the *total* distance the trolley has been pulled back from the catapult's zero point. (The zero point is where the trolley's post first touches the catapult.)

Plot a graph of FORCE (upward) against DISTANCE (along). The area under such a graph represents the WORK which measures the transfer of energy *FROM chemical energy* in our muscles *TO strain energy* in the catapult. To show why this is so, take a small part of the total-distance-pulled-back and draw vertical lines up from that to the curve that has been plotted from measurements. The area of that pillar is the WORK for that small bit of the potential energy stored. It is the FORCE AT THAT STAGE × THAT SMALL DISTANCE MOVED.



Then the total area under the graph—from the beginning of the loading process (when the post on the trolley first touches the catapult) to the position where we hold the trolley ready to launch it—gives the total ENERGY STORED in the catapult before launching.



Each pupil plots a graph and estimates the energy stored, by measuring the area under his graph. Then all members of the class compare notes.

(ii) Measuring the K.E. given to the trolley Pull the trolley back, *stretching the catapult the same amount as before*. Release the trolley and obtain a tape record of its speed, v, *after it has left the catapult*. Measure the trolley's mass m. Calculate the trolley's K.E. $\frac{1}{2}mv^2$.

(iii) Compare the two forms of energy. Does the K.E. gained agree with the energy given up by the catapult? This experiment is by no means easy: and we should not expect more than rough agreement.

Demonstration 58 Table tennis with a trolley started and stopped by catapults: energy changes

Apparatus

1 dynamics trolley	item 106/1
1 runway	107
rubber bands	233
1 newton spring balance	81

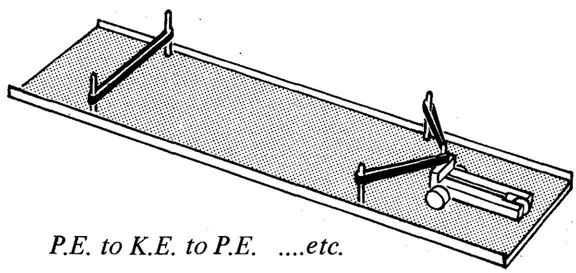
Procedure

Fit the runway with a catapult at each end (as in Expt 59).

Compensate the runway for friction *without* tape. Timer and tape are not needed for this.

Set up a catapult at each end of the runway, with equal rubber bands. Calibrate each of them with a newton balance. Record measurements of force and distance. Plot a graph for each, to find energy stored.

Let the upper catapult project a trolley along the runway. It runs till it is stopped by the other catapult.



P.E. to K.E. to P.E. ....etc.

Note how far the trolley was pulled back before release; and how far the second trolley pushes back in stopping.

From the graphs calculate the *strain energy* lost by the first catapult and the *strain energy* gained by the second one. How do those two lots of energy compare?

If the rubber band catapults are closely matched, simple measurements of total distances pulled back and pushed back may match well enough to convince beginners who find the detailed assessment from graphs too complicated.

Class Expt 59 Table tennis with a trolley started and stopped by catapults *(Pupils' version OPTIONAL)*

Apparatus

Each pair of pupils wishing to try this will need the apparatus listed for the Demonstration.

Procedure

Pupils follow these instructions:

* * * * *

Compensate your runway for friction *without* tape. You do not need timer and tape for this.

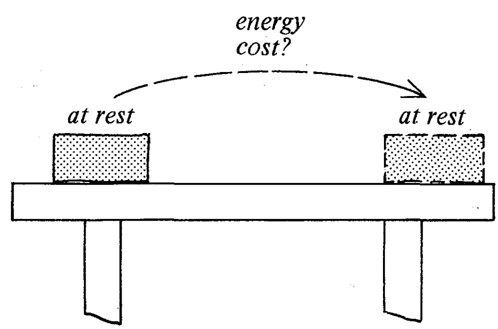
Set up a catapult at each end of the runway. *Make sure your catapults are closely matched.*

Then you can just measure the total distance the first catapult is pulled back at the starting end and the total distance the other one is pushed back at the finish.

Do these match? Discuss the result with your teacher.

* * * * *

What does it cost to move an object across the table? Living in a world where there is plenty of friction, pupils are apt to think that energy must always be supplied to move an object from one place to another at the same horizontal level. Pupils will say dutifully that the potential energy of a brick at one end of the table is the same as its potential energy at the other end. They will agree that if the brick is at rest in the first position and again at rest in the second it has gained neither K.E. nor P.E., yet they feel uneasy when we say the voyage from one position to the other requires no energy.



In fact, unless we are prepared to allow it infinite time, the voyage does require some energy, temporarily, on loan from some store. To get across in a short time the brick must move quite fast; it must have some kinetic energy; but at the end of the trip we can get that energy back.

Although the catapult experiments illustrate this, a demonstration in which a small falling weight provides the loan of energy seems to make things much clearer to many pupils. See the sketches opposite.

Arrange to borrow some P.E. from a small load high up, to give K.E. to a trolley which then runs along the table. As it approaches its destination the trolley pays the energy back by raising the small load again as it slows to a stop.

Demonstration 60 Free transport from here to there along the table by borrowing some K.E.

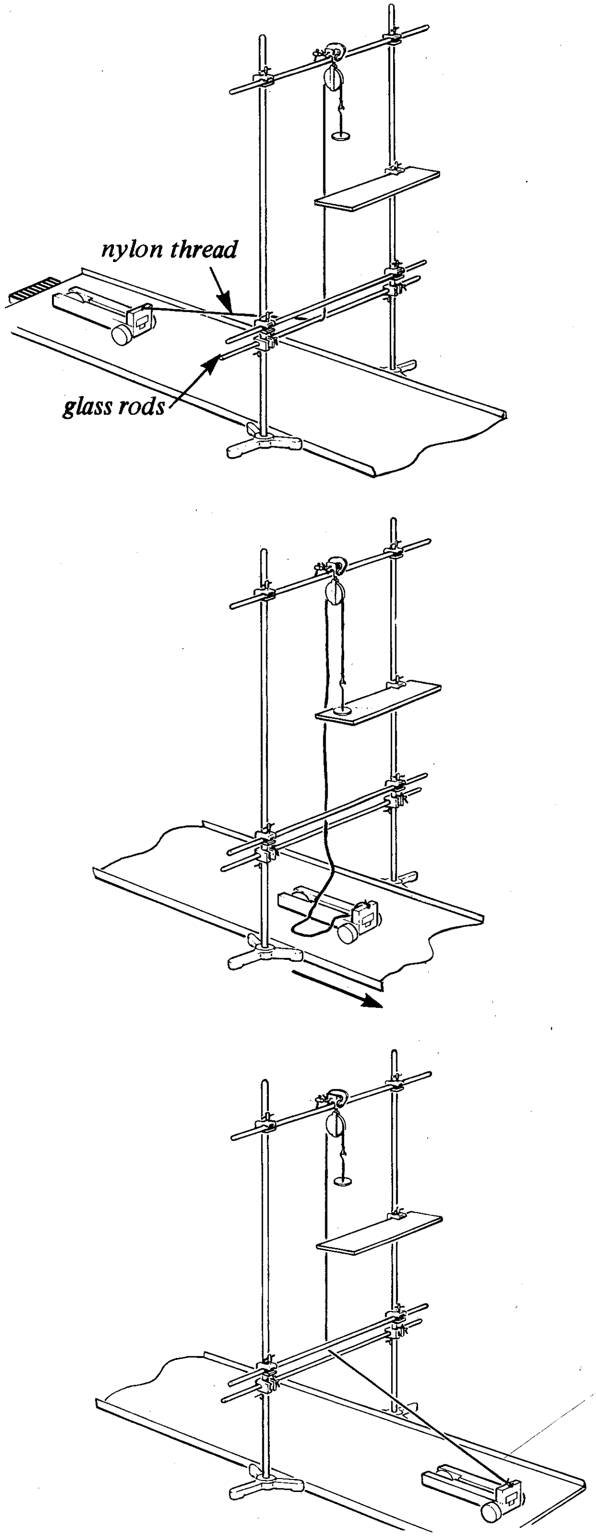
Apparatus

1 runway	item 107
1 dynamics trolley	106/1
1 single pulley on clamp	40
2 retort stands	503
2 or 4 glass rods	
8 bosses	505
1 10-gram hanger	31/1
1 large G-clamp	44/1
1 small G-clamp	44/2
1 wooden platform	
thread	

Preparation

Compensate the runway for friction, without tape. Halfway along the runway, arrange stands and platform and pulley, as in the sketch.

Place a 10-gram load on the platform. Run a thread from that load up over the pulley and down between the pair of horizontal rods; then fasten the end to the trolley.



The rods must be close together and at such a height that a trolley moving along the runway will just clear them. The thread must be just long enough for the trolley to be about 30 cm from the pair of rods, when the load rests on its platform.

Procedure

Pull the trolley back so that the load is raised almost to the pulley. Release the trolley. It is pulled by the descending load for the first part of its travel and then proceeds at constant velocity. Towards the end of the trolley's run, the thread tightens again and the load is hauled up. How high does it rise?

Failure? Ideally, the load should rise to its original height. In practice, friction takes a large toll. There are also unavoidable, unseen losses of K.E. in the inelastic events of the thread's pulling taut, and of the load's arrival on the platform.

This will have to be an 'experiment of principle', to illustrate an idea, rather than one with a convincing measurement. However, there are limits to its acceptability even in that guise—if the efficiency is below 60% the experiment is not worth showing.

To minimise inelastic losses keep the mass of the pulling load quite small by comparison with the mass of the trolley.

The friction at the rods can be lessened by using glass tubes on knitting needles as rollers.

Demonstration 61 Massive pendulum to show energy changes

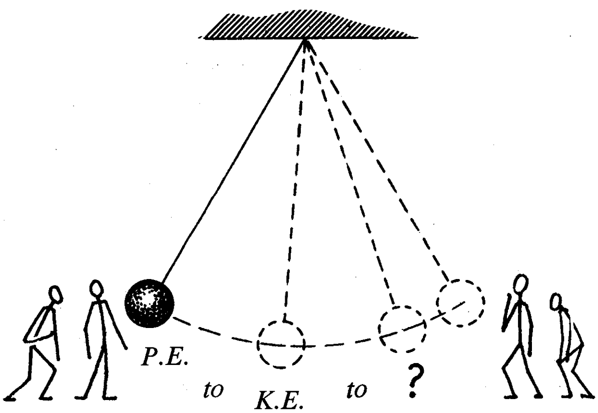
Apparatus

1 massive pendulum

A 5-cm steel ball (item 131B in Year 4 General Kit) could be used as the bob; but a more massive bob such as a large brick or a 5-kg 'weight' is much better. The bob is best suspended by thin steel wire from the ceiling. The *support* at the top must be massive and rigid.

Procedure

a. Draw the pendulum to one side, release it and let it swing.



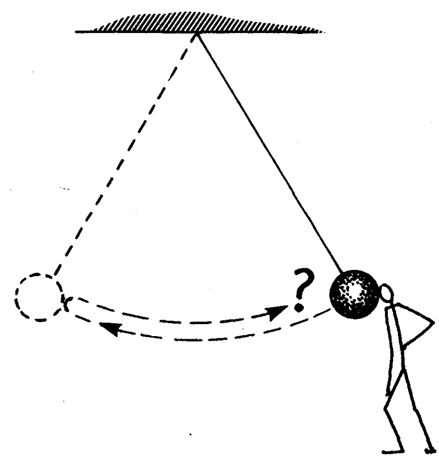
Discuss energy-changes from P.E. to K.E. to P.E. and so on.

There is no way in which energy can be lost through the thread of the pendulum, unless its support is insecure; so we expect that all potential energy lost when the pendulum bob swings downward will turn into kinetic energy. Therefore, if we know the height of rise of a pendulum from lowest point to its starting point at rest, we can calculate its K.E. at lowest point, and thence its speed there.

Point out that this also applies to a frictionless trolley running down a hill of *any* shape; to a car on a big dipper, or even to a marble rolling to and fro in a bowl—though this involves spin-energy too.

(Newton knew this property, though he did not discuss energy as such, and he used it to calculate the speeds of pendulums at their lowest point when he was investigating Conservation of Momentum. He did some very ingenious experiments with colliding pendulums, making clever allowances for air friction. He calculated the momentum of each of his two pendulums before and after collision and assured himself of momentum-conservation. He tried pendulums of many materials—including one with wheat inside, in case organic materials had a different behaviour. This is not something that we need disuss with pupils but it is an interesting matter to have at the back of our minds for teaching. Newton's own account in the *Principia* is impressive.)

b. As a dramatic demonstration pull the pendulum aside and stand so that it just touches your head. Then let it go and stand quite still until it returns.

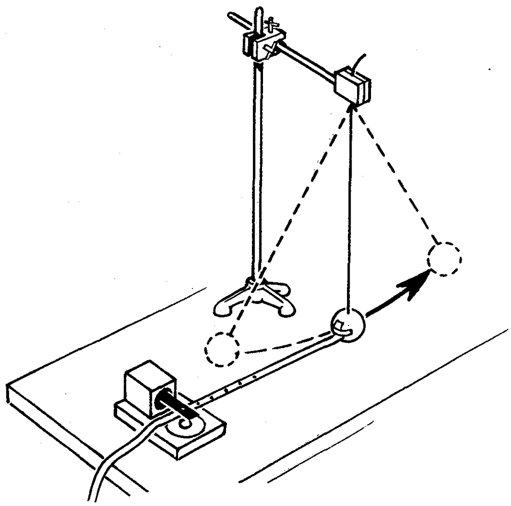


c. Optional buffer experiment In a very fast group, pupils might measure the speed of the pendulum bob at its lowest point and compare it with the value predicted by assuming that [P.E. lost] is equal to [K.E. gained].

Pupils measure the difference in the bob's height between the end of its flight and the middle. They calculate the P.E. lost. (They need not weigh the bob. They may call it mass m, and will find the m occurs in the K.E. and in the P.E. so it cancels out in the calculation of v.)

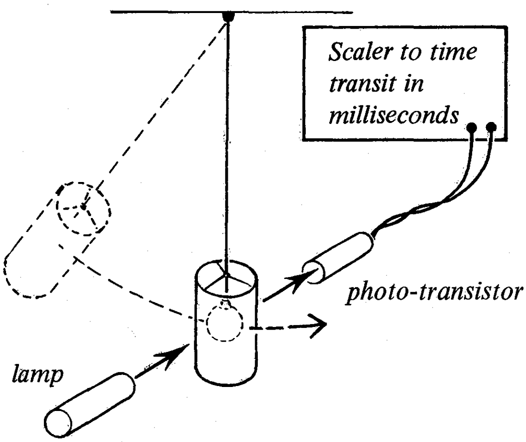
Let two keen volunteers* measure the maximum velocity directly by attaching ticker-tape to the bob (using Sellotape) so that it is pulled through a vibrator.

* They will take a week and learn a lot.



d. Optional demonstration of speed Instead of using ticker-tape, use the scaler (item 130/1) to measure the maximum velocity. Set it up with the photo-diode connected to the make-to-stop terminals.

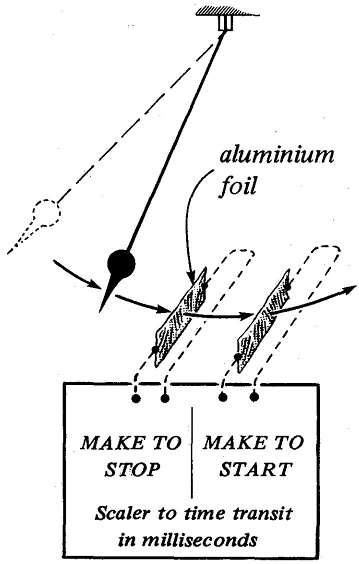
The beam of light might miss some of a spherical bob's full diameter. To avoid errors due to that, make the bob cylindrical or install a cylindrical collar of cardboard round it. Arrange



the pendulum, photo-diode and lamp so that the cylinder passes between the lamp and the photo-diode when the bob is at its lowest point.

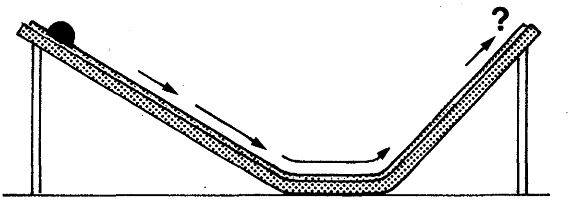
The pre-focused lamp illuminates the photo-diode. The scaler records the time the cylinder takes to pass the photo-device; and from that its velocity can be calculated.

e. Alternative method for speed-measurement Attach a spike to the bob and let it break two strips of foil, placed 10 cm apart, connected to the scaler as in measuring the speed of a rifle bullet. Breaking the first foil, connected to the make-to-stop terminals of the scaler, will start the 1000-Hz clock; breaking the second foil, connected to the make-to-start terminals, stops the clock.



f. Take a multiflash photograph of a swinging pendulum and analyse it. Attach a small lamp bulb and battery to the bob (or use them as the bob). Take a multi-glimpse picture.

Galileo's foresight Remind pupils of Galileo's downhill and uphill idea (described in Year 3 and suggested this year in Chapter 3). Galileo assured himself, by drawing upon his common-sense knowledge of nature, that an object sliding or rolling down one hill and up another would reach the same height on the opposite hill—apart from effects of friction. He believed this would hold in general, *whatever the slopes of the hills.*



That idea led Galileo to what we now call Newton's First Law. Galileo also used it as a starting point for his theory of forces and motion on an inclined plane—which gave a hint towards Newton's Second Law.

But we can also see Galileo's idea as a forerunner of the conservation of [K.E. + P.E.]. Therefore unless pupils have seen them recently and remember them well, they should see the demonstration of a ball rolling down one hill and up another—with friction taking a regrettable tax—and then Galileo's brilliant version with practically no friction.

Demonstration 62 Downhill-and-uphill motion: Galileo's guess *This is the same experiment as Demonstration 33, with a new moral: it throws light on energy-conservation.*

Apparatus and Procedure

See Demonstration 63 in *Teachers' Guide 3*.

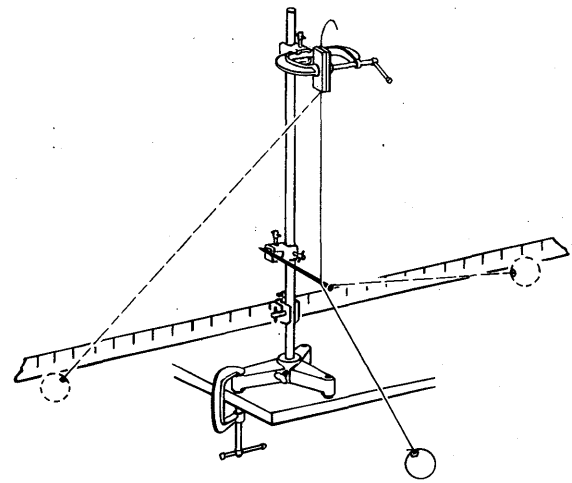
Galileo's stroke of genius Friction makes the demonstration unconvincing. Galileo, three and a half centuries ago, devised an almost frictionless version. Instead of a ball that falls by rolling down a hill, he used a ball that falls by swinging down as a pendulum.

Demonstration 63 Galileo's pin and pendulum: frictionless experiment

This is the same experiment as Demonstration 34 with a new moral: it throws light on energy-conservation

Apparatus and Procedure

See Demonstration 64 in *Teachers' Guide 3*.



When they see these demonstrations, pupils may themselves offer an energy argument and point out that the P.E. that turns into kinetic energy should go back into the same amount of P.E. (except for friction) so that the ball 'should' or 'ought to' or 'must' rise to the same level. That 'should' seems to beg the question, though it would be sound if we could be assured of the Conservation of Energy by some *other* means.}

{In fact, our belief of conservation of [P.E. + K.E.] is derived, on certain assumptions, from Newton's Laws of Motion—Laws which Newton derived from Galileo's thinking and experimenting with motion on hills—and it is a calculation of WORK, from Newton's Second Law that provides us with $\frac{1}{2}mv^2$ for K.E.}

{So, logically, motion on hills, Newton's Laws and Conservation of Energy are inter-connected; and we should be careful not to explain them in a circle. Nevertheless young people who of their own accord point out any connection here, deserve high praise and should not be worried by doubts of logic.}

Demonstration 64 Kinetic energy disappears: inelastic collisions

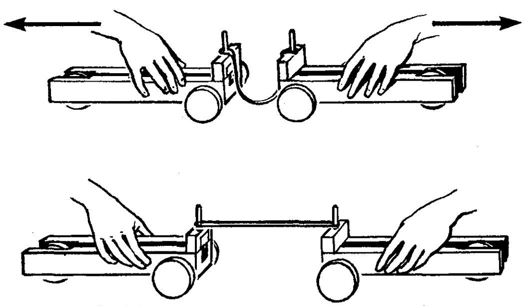
Apparatus

2 dynamics trolleys	item 106/1
2 elastic cords ‡	106/2
1 large pin and cork	
2 wood dowel posts	565

‡ In place of the elastic cords, a weak spiral spring of good steel wire could be used; e.g. an expendable spring from the Elastic Materials Kit (Year 1) pre-stretched into an open weak spring.

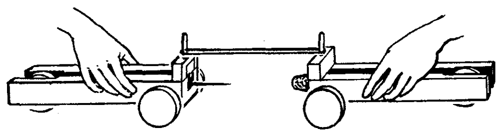
Procedure

a. Place two trolleys on the bench with one or two elastic cords held between them, secured over a wooden dowel post on each of the trolleys. Start with the trolleys close together with the elastic slack. With a hand on each give them outward motions and let go, so that they move apart. The elastic stretches and brings them to rest; grasp them and hold them in those positions.



Ask where the energy has gone. Then release the trolleys so that much of the kinetic energy is regained.

b. Vary the experiment by starting with the trolleys well apart and the elastic stretched. Release them so that the trolleys meet with a bang. Again ask where the energy has gone.



Repeat with a large pin sticking out of the end of one trolley and a cork attached to the other so that the trolleys stick together on collision. (To fix the cork, it may be easier to fix a pin on each trolley and then fix a cork on one of the pins beforehand.) The potential energy stored in the elastic disappears; and the kinetic energy disappears. Where has the energy gone?

c. Repeat (*b*) using the trolleys with a spring-loaded buffer-rod protruding from one. When the trolleys collide, they move apart, are brought to rest by the elastic, then return and collide again. This process will be repeated several times before they finally come to rest. Again discuss where the energy has gone.

These experiments and discussion following them in *Pupils' Text* Chapter 5 are intended to lead to ideas of heat being in some way associated with energy—and the full story comes in Chapter 9.

SECTION II

GASES

We now return to the Molecular Theory of Gases treated more quantitatively.

Chapter 6 in *Pupils' Text* is a chapter for all pupils in Year 4. It ranges from simple description to simple imaginative theory. We hope it will give all pupils a feeling for scientific thinking.

Then Chapter 7 takes a more orthodox view and expects pupils to watch an algebraic derivation of the kinetic-theory expression for gas pressure; and then to follow a prediction. In examinations, candidates would be expected to understand the general lines of thinking but they would not have to produce the mathematical argument in full.

The third chapter of the trio on Kinetic Theory, Chapter 8, remains in our suggested programme although many pupils will find parts of it too difficult. A teaching programme of kinetic theory which ended with a formula for pressure—put to no use—would be a poor exhibit of scientific theory for young people. Having made assumptions, and applied some rules and derived an expression, we must show the theory being fruitful. Our teaching must carry pupils on to predictions and measurements of some components of the theory itself. Pupils should make an estimate of molecular speed (Chapters 6 and 7); they should consider theory's prediction of Boyle's Law, with the supporting test of the speed of sound (Chapter 7); and we hope some of them will go on to see how we can estimate mean free path and thence the size of a molecule (Chapter 8). Then the Avogadro number is seen to come from visible measurements and not just from a book of data.

The arguments involved in these latter developments are difficult—a challenge to pupils to reach up to them, just for the moment, and a challenge to teachers to show them as a special performance to be remembered with insight—but not to be recalled with algebra.

CHAPTER 6

GASES 1

Models for catching up; Simple molecular pictures; A model to suggest Boyle's Law; A simple prediction of molecules' speeds

If this chapter seems unjustifiably long, note that more than half of it is concerned with 'catching up' experiments and discussion that may have been left out in Year 3.

MOLECULAR PICTURE: SOLIDS, LIQUIDS, GASES

Remind pupils of the earlier picture of the three common states of matter, in each case made up of small particles—atoms or molecules—but with different amounts of arrangement (well ordered crystal, short-range order, random disorder) and different types of motion.

If we feel we are well into the thermonuclear age, we may want to describe one more state of matter: a 'plasma' of electrons and bare nuclei.

Solids In solids we picture atoms or groups of atoms arranged in a regular 'lattice', like the patterns of a wallpaper, but in three dimensions. They are held in that lattice by strong forces—attractions at short distances—which give the solid its strength. We now know that all those forces are electrical forces arising from the charges in atoms, subject to the ordinary inverse-square law of forces between charges, but disciplined by some quantum rules as well.

The atoms in a solid are in constant motion, vibrating in various directions with vibrations of characteristic frequency and with amplitude determined by the temperature.

Show again a model of atoms in a crystal, represented by small balls joined together in a cubic 'lattice' by weak springs.

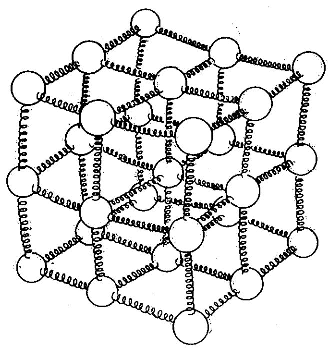
Demonstration 65 Model of atoms in a solid

Apparatus

1 model of atoms in solid — item 22

Procedure

The model will already have been shown in earlier years, but it should be shown again here and made to vibrate.



This model, rather like a three-dimensional spring mattress, illustrates the structure of a solid but it does not show the complexity of vibrations very well.

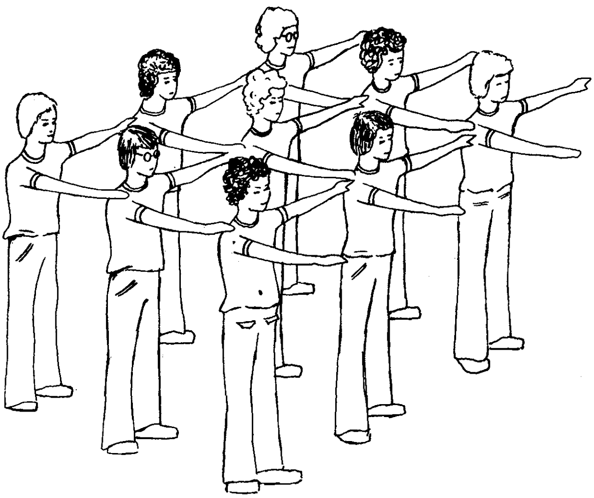
At higher temperatures, vibrations of atoms in solids may carry them so far out in the range of atomic forces that the ties are too weak to hold them in their well-ordered arrangement, and the solid melts.

A teacher who does not mind considerable confusion, can make a good model of this with the whole class of pupils acting as molecules or atoms in a crystal.

Expt 65 Model of a solid using pupils

Procedure

Pupils stand in a regular array with arms stretched out to hold the shoulders of neighbours. Ask them not to stay at 'absolute zero' (at which on simple classical theory they would have no vibration at all—though on modern theory they would have a little vibration). They should 'warm up to room temperature' and vibrate to and fro.



If we allow the model to go to higher and higher 'temperatures', the solid will eventually 'melt' as the crystal comes to pieces.

For a model of molecules in a liquid, pupils stand an arm's length apart with arms folded, moving about as a fluid crowd.

The full story of heating a solid is more complicated than the simple one of just making the amplitude grow as we warm up the model atoms, because there is a quantum-restriction on the way in which an atom can carry vibrational energy. The restriction does not make itself felt in ordinary measurements, such as specific heat capacity, at room temperature. But at low temperature when atoms are 'poor in heat' the currency restrictions of quantum rules make themselves felt and specific heat capacities drop to unexpectedly low values—a behaviour that could not be explained on classical theory, and itself helped to point to the quantum restrictions.

None of this need be said to pupils; yet it is something to keep in our minds as a link between our talk now about motion of atoms in solids and our teaching at A-level of a quantum theory which is so powerful in modern physics that we cannot ignore it.

Liquids In a liquid the atoms or molecules are not much farther apart but they often move out of the strong field of force of a neighbour for a short time—though they soon move into another strong field—so that the regular order is not maintained on a wide scale. Molecules can move past each other and collide with neighbours so that the liquid behaves in its characteristic fluid way.

If we consider this carefully, we may come to doubt whether the liquid can have lost all sense of order and regimentation. If it has, it is really only a very highly compressed gas, and we know that liquids are different from this, because we can have a bottle containing liquid in its lower part and vapour above it—a two-phase system which we could hardly imagine if the liquid itself were an entirely disordered random system. In fact, liquids do show some local short-range order, but they do not have the completely organised state of a crystal, so they form, as seen through our macroscopic eyes, disordered fluids.

† **Model of liquid** Pupils return to the tray of marbles, used as a two-dimensional model of a gas. They tilt it to simulate a liquid and look for 'diffusion' and for 'evaporation'.

If it is treated as a silly toy, the tray will fail to show much in this experiment; but if pupils *want* to use it for a good model they will find that with careful choice of tilt and agitation they can make this experiment very fruitful. It will help when we wrestle with an important question in our estimate of molecular size in Chapter 8: *'How close can molecules be crowded together and yet show the fluid behaviour of a liquid?'* We need a very rough guess.

LIQUIDS AND EVAPORATION

† Class Expt 66 'Teaching model' to represent a liquid

Apparatus

1 two-dimensional kinetic model kit item 12

Procedure

Pupils follow these instructions:

* * * * *

Put enough marbles in your tray to fill it at least a quarter full. Keep the tray slightly tilted so that all the marbles run down to one end (without running on top of each other). Agitate the tray gently with one edge on the table top. Watch the motion of the marbles.

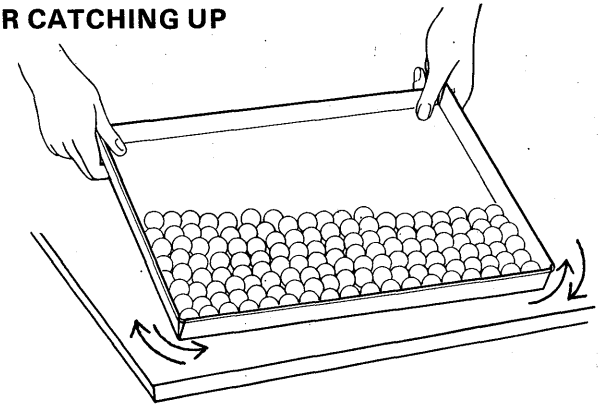
Watch a marble 'evaporating' from the 'liquid' of marbles in the tilted tray.

Think about a real molecule evaporating from the surface of a liquid. The molecules of a liquid attract each other: they must do this, or liquids could not hold together in drops.

Also watch the progress of one marked marble in the 'liquid'—we call this diffusion.

* * * * *

Energy changes: solid ... liquid ... vapour The density of most substances is almost the same in liquid state as in solid. So we picture the atoms or molecules in a liquid almost as crowded as in a solid. But in a solid they are locked in a crystal pattern by strong forces; so we expect



to spend some energy when we tear the atoms of solids away against strong local attractions and make a liquid. That is the latent heat of fusion, the thermal energy we must supply to effect melting without any temperature change.

Yet we should hardly expect this demand of energy to be as big as the demand for tearing the molecules of a liquid away from each other into vapour, since in melting, the molecules do not move out of the range of attraction of neighbours; in vaporisation they move far out of range, after moving farther against attractive binding forces.

(Compare 0.34 megajoule to melt 1 kg of ice with 2 to 2.5 megajoules to evaporate 1 kg of water.)

GASES

Gases In our picture of vapours and gases we must imagine that there are enormous spaces between one molecule and the next (*unless* the change from liquid has somehow made molecules swell up enormously or else made them multiply). The volume-change—something like 1 to 1000 from liquid to gas—tells us that the spacing-apart must have increased enormously.

Ask pupils how far apart the 1:1000 expansion would carry molecules from the liquid pattern where they are practically 'in contact', about one diameter apart centre to centre.

We should not at this stage *tell* pupils the answer; but teachers have found that some pupils suggest it easily: the cube root of 1000. Give praise for such an answer but ask those who know it not to 'give the show away' to others.

That kind of thinking-out of new knowledge from a given piece of information is good science; and we should do everything we can to teach pupils that it is good science.

But just announcing results—*'science tells the answers'*—is a dangerous view, once people adopt it. It is not a description of real science. A more useful story, if we value the reputation of science, would run: *'Scientists find out. Scientists do experiments. Scientists do some thinking. Scientists arrive at more knowledge by hard work.'*

In gases, molecules are far apart; and they are probably moving fast, since they have considerable energy. Of course we might picture a set of stationary molecules exerting some strange field of repulsive force upon each other—and that was in fact what Newton suggested for air—but pupils who have seen the Brownian Motion are likely to favour a *kinetic* theory in which the gas molecules are moving about rapidly and can buffet a small speck of smoke ash.

The idea that bombardment by molecules makes air pressure, seems simple and sensible to us who heard it long ago. But it is a novel idea for many pupils; and they deserve an illustration to support it.

Demonstration 67 Model to show bombardment making pressure

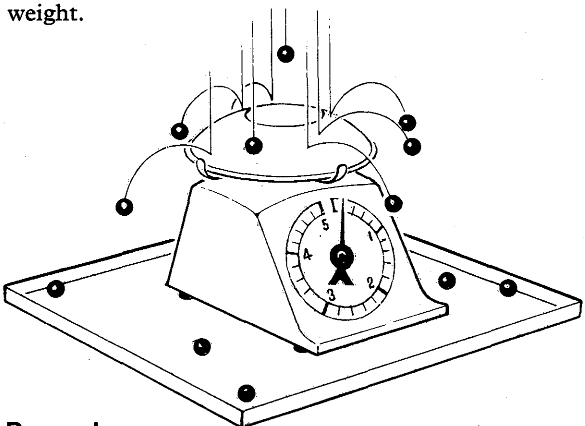
Apparatus

Toy shop marbles (or lead shot or steel balls)	item 12B
domestic balance ‡	20 or 206

‡ This experiment needs a balance in which the mass of the part that receives the impacts is small. A lever-arm balance would *not* be suitable. A domestic spring balance is suitable.

Preparation

Invert the scale pan or place an inverted bowl on it so that the balls bounce off without collecting and upsetting the readings by adding an accumulating weight.



Procedure

Place a large tray under the balance to catch the balls.

Pour a stream of balls by hand, from a height of $\frac{1}{4}$ to $\frac{1}{2}$ metre, onto the inverted scale pan on the balance. As the balls hit the pan and bounce off they exert small impulsive forces—like those due to gas molecules hitting a wall.

The comparatively great mass of the pan etc. smears out those forces into a steady reading on the balance.

Show this demonstration again before each form of derivation of molecular pressure.

When we ask: 'How can we put energy into a gas?' pupils are likely to say, 'Heat it'; and we should encourage them to interpret that as making an increase of the molecular motion.

Models Unless pupils are fully familiar with the models, show the three-dimensional gas model again now and give pupils the trays with marbles for further trials. Both these experiments throw more and more light on the molecular story as pupils grow more mature and ask more ingenious questions of the model.

† Demonstration 68a Model of air molecules: three-dimensional model for kinetic theory

Apparatus

1 three-dimensional kinetic model kit	item 11
1 fractional horse-power motor (or any small motor) with a belt	150
1 L.T. variable voltage supply	59
1 retort stand, boss and clamp	503–506

Preparation

Fix the rubber base over the lower end of the wide tube. Clamp the plastic tube in a vertical position.

Adjust the height of the tube so that the rubber base is 1 or 2 mm above the vibrating rod in its mean position.

The electric motor drives the vibrating rod. Connect the d.c. L.T. variable voltage supply to the armature terminals of the motor, and to the field terminals, in parallel.

Put the small phosphor bronze balls in the tube, so that they rest on the rubber base—enough balls to cover two-thirds of the base. The vibrating rod and rubber drum keep the balls in random motion.

Put the brass cap over the top of the tube: it prevents balls escaping and it cuts down the noise.

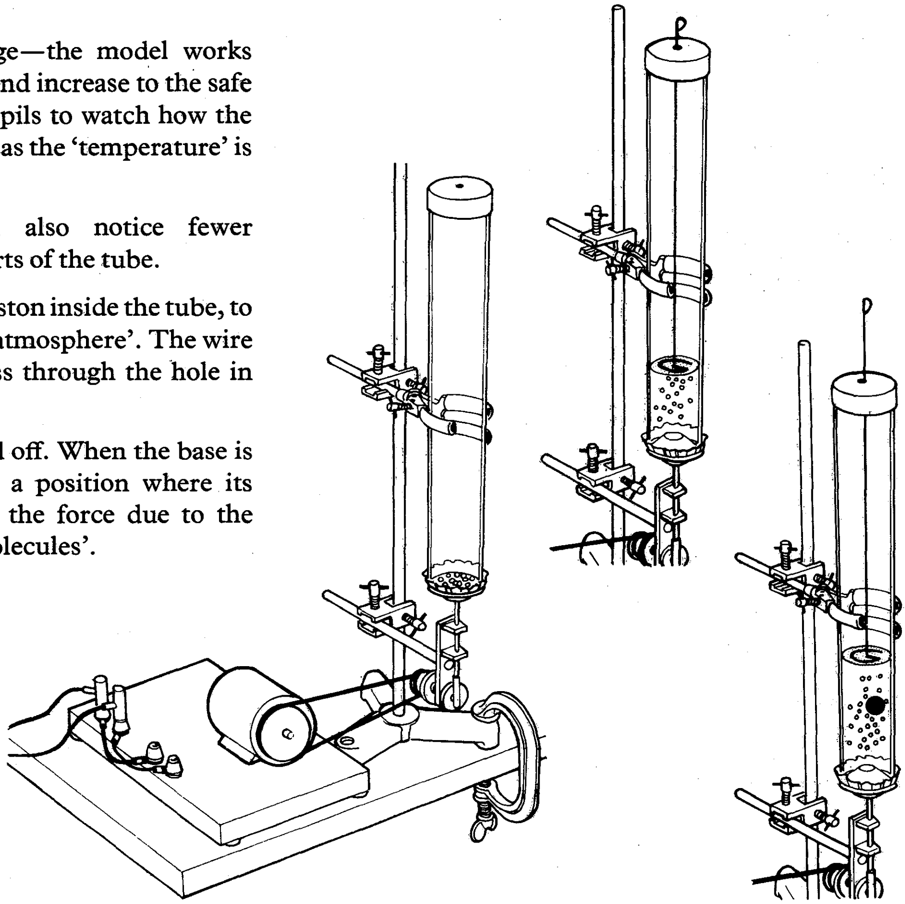
Procedure

Start with a low voltage—the model works effectively on 4 to 6 volts—and increase to the safe maximum, 12 volts. Ask pupils to watch how the atmosphere of balls changes as the 'temperature' is increased.

We hope pupils will also notice fewer 'molecules' in the higher parts of the tube.

Then install the paper piston inside the tube, to act as a movable lid for the 'atmosphere'. The wire holding the disc should pass through the hole in the brass cap.

Switch the motor on and off. When the base is vibrating, the disc rises to a position where its weight is just balanced by the force due to the pressure of bombarding 'molecules'.



Imitate the Brownian Motion by suspending a foamed polystyrene sphere among the small balls of the model.

Also 'raise the temperature' of this 'gas' by feeding more power to the driving motor. Ask what really determines the temperature of a gas; and move towards the idea that average kinetic energy would be a good measure.

(Some teachers like to place a translucent screen and lamp behind the demonstration to show it in silhouette against a bright background.)

(Like the two-dimensional model, this model already used in Years 1 and 3 will illustrate further aspects of gas behaviour in Year 4.)

Pupils' comments on the model If pupils complain that this 'gas' seems to need a continual supply of energy to maintain its motion, we may reply:

Yes it does, because the walls of its container are dead cold. The walls of the container of a real gas are as hot as the gas itself. The molecules of the walls are in constant vibration, and when hit by a gas molecule they 'give as good as they get'.

If you put a lot of hot gas in a room with very cold walls the molecules would indeed lose a lot of their energy. And that is what happens here with the model's 'molecules'; so we have to supply energy from outside if we want to keep them as hot as they are. (Also, when the model 'molecules' hit the rubber sheet at the base of the tube they make a rather inelastic collision, wasting some of their kinetic energy as heat.)

If pupils raise the question of the uneven distribution of molecules, point out that this is characteristic of a real gas and is what one would expect from chance collisions. If they raise the question of decreasing density with height, ask:

Why don't air molecules all fall down to the bottom of the container? Think of a small section of air half-way up; why doesn't it just fall down? The air below it must push it up with a bigger force than the air above it pushes it down. There must be more bombardment upward on the bottom of that imaginary chunk than downward on the top. And that means there must be a more crowded population of molecules below than above. An individual molecule must have a greater chance of being hit by another molecule moving upward than by one moving downward.

PUPILS' OWN MODEL OF A GAS

Any pupils who have not already played fully with the two-dimensional model of a gas offered in earlier years should try a variety of experiments with it now (Class Expt 68b).

†Class Expt 68b 'Teaching model' to represent a gas: marbles in a tray

Apparatus

Two-dimensional kinetic theory model kit	item 12
16 trays, with cork-lined bottom	12A
400 marbles (about 15 mm diam.)	12B
32 large marbles (about 25 mm diam.)	12C

Any rectangular tray will suffice, provided it has vertical walls and is fairly massive.

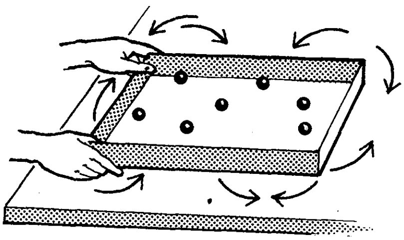
Pupils work in pairs. Each pair should have a tray and two dozen coloured marbles. Each tray should have one marble of a distinctive colour among the collection of other colours, so that pupils can watch its progress.

Procedure

Pupils follow these instructions:

* * * * *

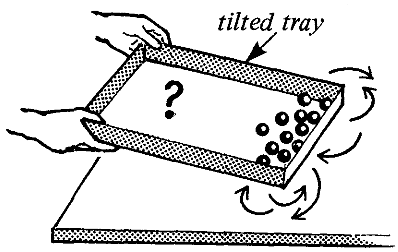
Put some marbles in a tray, to represent air molecules in the room—or any gas molecules in a box.



(i) Agitate the tray by sliding it about on the table with a rapid irregular shaking motion, to imitate the hot walls of the room.* Watch.

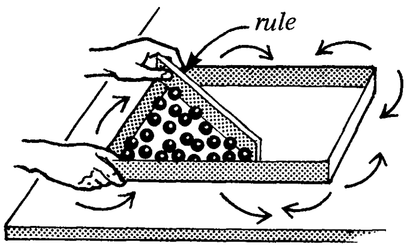
(ii) Illustrate a higher temperature. Agitate the tray more violently.

(iii) Listen to the sounds. Can you hear the different kinds of collision, some on the walls, others between marble and marble?



(iv) You can imitate the atmosphere (with its population thinning out higher up) by giving the tray a *very slight* tilt, and then keeping it tilted while you agitate it.

(v) For a model of a compressed gas, add more marbles and agitate the tray. Crowd all the marbles into half the tray, with a ruler. Continue to agitate the tray and see the gas expand when you remove the ruler.



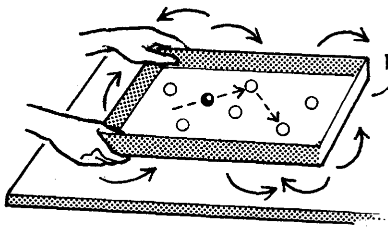
A convenient way to hold the ruler still is to place a small book in the tray and hold the ruler firmly up against it.

What is the effect of reducing the area further still?

* If the atoms or molecules in the walls of the room were not as warm as the air, but were completely cold, with little or no vibrations of their own, air molecules arriving at the walls would give up their kinetic energy and soon fall down to the floor. So, when using the tray of marbles as a good model, you should keep its walls in constant motion.

(vi) To make a model of a liquid, add still more marbles; tilt the tray to make 'liquid with vapour above it'.

(vii) There are still more things you can do, such as watching the progress of one particular marble.



* * * * *

As a special project, a pupil might gather statistics of velocities by taking photographs with a not-too-short exposure. (This has been done at university level as a research project.)

Expt 68X Photograph of marbles in motion
(OPTIONAL buffer experiment)

This experiment is only recommended for an enthusiast who wishes to experiment with photography.

Apparatus

1 two-dimensional kinetic model kit	item 12
1 camera	133
1 lamp	

Procedure

Place the tray containing a few marbles flat on the top of a bench. Illuminate it strongly by a bright lamp held above. Clamp the camera rigidly above the tray. Agitate the tray. Try photographing the moving marbles. This is easier if the bottom of the tray is black, and much easier still if the marbles are replaced by bright steel balls (about $1\frac{1}{4}$ cm diam.).

Find by trial the exposure that shows the track of each marble for a fraction of a mean free path.

The length of blur made by each marble provides a rough indication of its speed. Measure blurs and make a distribution tally.

BROWNIAN MOTION

Some pupils first see the Brownian Motion in Year 1. Others may have missed it, and they should certainly see it individually in Year 3, and even again now.

Those who saw it earlier may not have realised its full importance. So we suggest that all pupils who are now making a serious study of a molecular theory should see the Brownian Motion for themselves now, and discuss it—even if it is all repetition. It should be an experience that they now regard with fuller understanding.

First let pupils try the simple model, unless they remember it well; then the essential experiment—not as a demonstration, nor as a film, but as personal observation with a microscope. (The motion of particles in water would not be relevant as a substitute.)

Class Expt 68c 'Teaching model' of Brownian Motion: with marbles in a tray

Apparatus

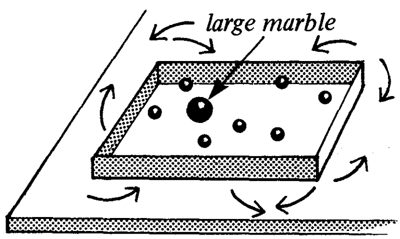
1 two-dimensional kinetic model kit	item 12

Procedure

Pupils follow these instructions:

* * * * *

Place a larger object, such as a bigger marble or a matchbox, among the marbles in your tray. Watch what happens to it when you agitate the tray. Compare its motion with that of the smaller marbles.



This suggests what might happen to something much larger than an air molecule, if it is floating in air. You can see this in real life by watching tiny specks of white smoke in air.

Description of equipment for Brownian Motion See *Teachers' Guide 3* for fuller description.

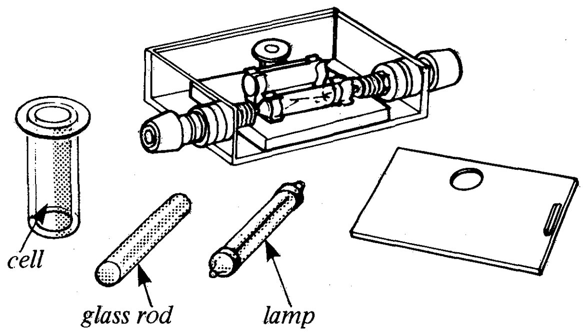
The microscopes must have an objective with a large aperture to take in plenty of light so that pupils see the motion of the smoke particles clearly. A high-power objective is not needed and is not even suitable. Any focal length between 10 and 30 mm will suffice (preferably the usual 18 mm), and eyepiece 10 ×. It is essential for the objective to have *large aperture*, and there must be sufficient clearance between the stage and the objective for the Whitley Bay smoke cell.

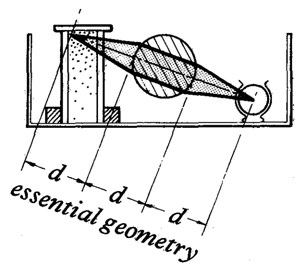
(Beware of the well-made, cheap, toy microscopes with claims of high magnification but small apertures.)

Whatever the cost in time and trouble, we trust microscopes can be borrowed and used with the smoke cell designed for Year 1.*

A considerable number of microscopes will be needed for a whole class: at least one for every four pupils. Otherwise there will be long queues and ensuing hurry; or else this will become a quick demonstration with each pupil getting only a brief look. We consider this is such an important part of learning about molecules and atoms that it should be a personal experiment which pupils see for themselves at leisure.

Teachers may find that pupils who have not seen this before take as much as 10 minutes to get used to their microscope and to look at the smoke and really understand what they are seeing, but it is worth this amount of time.





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* The Whitley Bay smoke cell (shown in the sketch) is so much easier for pupils to handle than other forms and makes it so much easier for them to see the Brownian Motion for themselves, that we hope teachers will put them into use. They are not difficult to make: a small lamp, a glass rod as a cylindrical lens, and a short vertical 'well' of glass tubing into which one pours smoke. A microscope cover glass serves as lid.

The lamp is a festoon lamp, used in cars. It is attached to the cell *so that the illumination cannot shift as pupils use the cell.*

The glass rod serves to focus light on the smoke. It produces a line image of the filament in the smoke.

To minimise convection, the lamp is placed *below* the level of the glass rod, so that the light slants upward and the brilliantly lit field of view is just under the lid of the smoke-well.

It is essential to arrange the optical distances as shown in the sketch.

†Class Expt 69 Brownian Motion of smoke in air: evidence of air molecules in motion

AIM: To give pupils a personal look at real Brownian Motion in air.

There should be one microscope for every four pupils.

Apparatus

8 microscopes (see special note above)	item 23
8 Whitley Bay smoke cells	29
8 transformers	27
8 squeeze bottles for smoke ‡(Now to be included in bromine diffusion kit)	81

‡ *Warning:* Putting smoke in the cell can be frustrating for beginners. Several methods have been suggested and tried:

a. A smouldering drinking straw, with the smoke running down through the straw to the cell. *The smoke (of wax particles) is too coarse and the straw diverts attention.*

b. Cigarette smoke from the teacher's mouth. *The smoke is damp and too coarse. Dry* smoke does very well.

c. Smouldering string or paper, or a match or cigarette held just above the top of the cell; or the smoke transferred by eye dropper. *Good.*

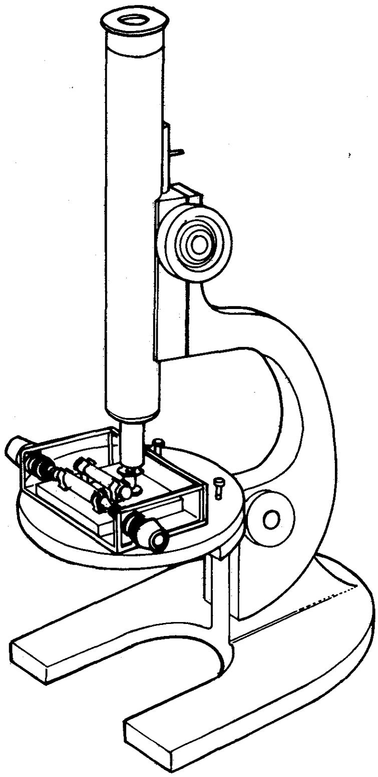
d. A squeeze bottle filled with smoke and pressed *gently. This is best.* A polythene wash bottle serves well for this. A piece of smouldering rope (or brown paper) provides the smoke; but if it touches the wall of the bottle the wall may melt; so the rope must be held by clips to the central tube in the bottle. A very gentle puff provides more than enough smoke.

Pupils may have trouble managing the smoke bottle and they are apt to puff out too much smoke; so, as the filling with smoke is not a major part of the experiment, we suggest that the teacher carry a smoke bottle round and fill each smoke cell, at least for beginners.

Preparation

Make sure that the old smoke ash has been cleaned out of the smoke cell itself.

Place the cell on the microscope stage *and clamp it there* if possible. Connect 12 volts from the transformer to the terminals on the smoke cell.



Procedure

Pupils follow these instructions:

* * * * *

Light the end of a piece of rope and put the smouldering material in the squeeze bottle.

Remove the cover from the smoke cell and inject a little smoke into the cell.

Slide the cover on and focus the microscope on the cell.

Smoke is made up of tiny specks of white ash. You will see a strange motion; and you may well believe you are seeing the effects of bombardment by air molecules.

We name this motion after the botanist Brown who discovered it. (He probably thought at first he was seeing living things.)

* * * * *

Warn pupils that there are convection currents ('breezes of warm air') which carry the whole army of particles drifting across the field of view; and that the drifting motion is not what we are looking for.

Also explain that particles out of focus make large round patches of light. These characteristics seem simple enough to us but can spoil the experiment if pupils are worried by them.

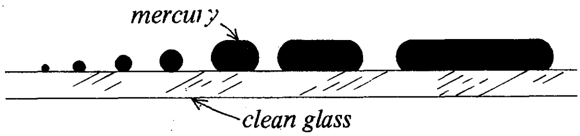
Heat and motion We might suggest, for the moment, that all the increase of energy when we churn up a gas (or compress it, or pass it over heated metal) can be accounted for as extra energy of motion* of the molecules. We use this concept in discussing evaporation.

* Molecules which consist of more than one atom also store some energy in rotational motions and in vibrations, but the patterns of these changes as temperature rises are more complex.

† ENERGY AND EVAPORATION

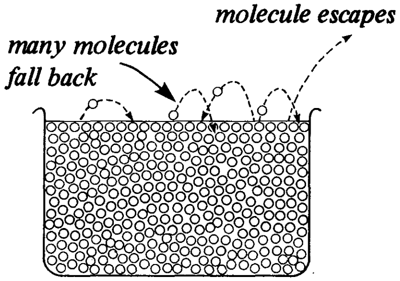
We suggest teachers should not spend much time discussing vapour pressure, boiling, etc. These are interesting descriptive parts of physical science but pupils' progress into atomic physics and other modern topics will not be seriously hurt if change of state is not treated in detail. Yet now that we are discussing energy and molecules we should certainly ask what happens, *from the point of view of molecules*, when a liquid evaporates.

Ask pupils how they know that molecules in a liquid attract each other—hoping for the answer 'surface tension'. Unless a molecule in liquid is attracted by near neighbours, we could hardly expect a liquid to hold together and show the tight 'skin effect' of surface tension. Pour some drops of mercury on a clean glass sheet in a demonstration projection lantern and let pupils see how little the shape of the smaller drops is distorted by gravity.



In a gas, the molecules are too far apart (unless it is very highly compressed) to feel the attraction of their neighbours except for a negligibly short time near a collision.

Physicists know this because real gases at ordinary densities fit closely with Boyle's Law, which theory predicts for molecules with negligible interaction. (Put twice as many molecules in a box and, provided they do not interact, we expect double rate of bombardment, therefore double pressure—Boyle's Law.) We can hardly give that argument to pupils at this stage; but we should tell them we have reason to believe gas molecules do not attract noticeably.



Evaporation

When a liquid evaporates, molecules leave its surface. Think about a molecule which has just left the surface and is still very near to neighbours in the liquid. It must feel some attraction from those neighbours, pulling it back into the liquid. In fact, many a molecule that does leave the surface falls back in—much as many a projectile flung up from the Earth falls back to it (see Experiment 66). Only a few, flying out extra fast, have enough energy to get away altogether. Those are the molecules that evaporate.

There is no mysterious influence *pulling* molecules out from a liquid towards the space outside. All that happens is that some molecules near the surface gain enough outward speed from chance bombardments by neighbours.

(For molecules in a liquid there is an average kinetic energy of their jostling motion which is much the same as the average kinetic energy of a gas molecule at the same temperature. There must be many a molecule with average kinetic energy in the surface layers, and some of these must be moving outward at any instant. These do not have enough energy to get away—in modern terms their speed is below escape velocity. Only some molecules which happen, at the moment, to have *much more than average* K.E. can escape.)

(We know this for two reasons:

1. If the *average* energy of a liquid molecule were sufficient for escape, we should expect the whole liquid to come to pieces: the liquid would behave almost like a gas. That does not happen until we heat a liquid to a certain high temperature which we call its critical temperature.

2. When there is evaporation, the remaining liquid is left colder. Evaporation is a cooling process. From that we infer that the molecules that do escape take away more than an average share of kinetic energy. Then since 'extra rich' molecules have left, the remaining population of molecules in the liquid have less kinetic energy, on the average, than before.)

Cooling by evaporation The second comment on evaporation is so important that teachers should discuss it with pupils—unless it was treated in Year 3. Remind pupils that surface tension effects tell us that liquid molecules do attract each other when close. Describe evaporating molecules escaping, and lead to the idea that only 'extra fast' molecules will escape successfully, carrying away an extra large share of kinetic energy, therefore leaving the liquid cooler.

Then point out the importance of evaporation for human beings. Our open skin is slightly moist and evaporation enables us to avoid overheating: it plays a very important part in maintaining an even temperature. Drops of perspiration that drip from our brow do no cooling; but, if the surrounding air succeeds in carrying away water molecules that evaporate, we are cooled. In a very crowded room, the air soon becomes so damp, so full of water vapour, that water molecules return to a damp brow as fast as they leave. Then there is no cooling; our temperature goes up, and we feel uncomfortable. The stuffy feeling of a crowded room is not due to increased concentration of CO_2: it is due to damp air preventing successful cooling by evaporation, so that we develop a temperature.*

Rapid evaporation from our skin provides much more rapid cooling than a cold bath. That is why one can catch cold so easily by walking around in damp clothes. A macintosh worn on top of the damp clothes to stop the evaporation, can greatly lessen the chilling, though it is uncomfortable.

PROGRAMME

Talk with pupils about their programme ahead, in this chapter and in Chapters 7 and 8. They are now in a position to think quantitatively about molecules in a gas. They will soon be able to predict the pressure of a gas in terms of mass and speed of molecules. Then they can reverse that and estimate molecular speed from sample measurements of air density and pressure.

Pupils will see that the 'constant' in Boyle's Law is proportional to the total kinetic energy of all the molecules in the sample. From that they can see that it is at least reasonable to use the kinetic energy of a molecule as a measure of temperature. And they can see, from the predicted form for pressure of a gas, that the molecules of dense gases must move slower than those of light gases. Having predicted that, they can see it illustrated by diffusion demonstrations.

{This should make a thrilling expansion and consolidation of earlier, much simpler, studies of gases. It should not turn into a discouraging drive through algebra that is too difficult for slower pupils, or into a period of pupils' memorising things that seem too complicated to learn with understanding. In the latter case it would be better to leave kinetic theory of gases in the simpler form of earlier years. However, we find that pupils who see that they are making a very important exploration in the world of molecules, *can* take the trouble—and *want* to take the trouble—to surmount the difficulties of algebra. They themselves think this a mountain worth climbing.}

* For evidence see Wells, Huxley, Wells, *The Science of Life*, section on 'Air of a stuffy room'.

{We can even offer pupils a chance to estimate the size of a single gas molecule, and thence the number of molecules in a known volume at known temperature—e.g., the Avogadro number. Pupils will need courage to follow the quite difficult reasoning and imaginative thinking that go with the simple experimental measurements. For this estimate we measure the progress of bromine diffusing through air; and from that arrive at the mean free path of gas molecules from which we estimate the diameter of a single molecule.}

DISCUSSION OF TEACHING POLICY

{This is a stage at which young physicists should not just collect data and give interesting descriptions and formulate descriptive models; this is a time for more definite knowledge and some use of mathematics, the necessary tools of physics. So we should somehow, at this stage, show how physicists treat the vast horde of molecules that they imagine there to be in a gas—how they use Newtonian mechanics with some simple algebra and some simple averaging, to arrive at a definite prediction which can be turned to good use. We wish to show pupils how physicists predict $PV = \frac{1}{3}Nmv^2$.

{This is not a result to be memorised, nor should the full argument of 'deriving' it from simple assumptions be learnt by heart as something that can be produced in an examination without the candidate knowing quite what he is doing. Somehow, we want every pupil to feel he knows what he and the teacher are doing when they arrive at that statement. That suggests, for one thing, that we should use different methods for classes of different ability; and for another thing, that we should stimulate and encourage pupils to follow such a story through with the teacher without expecting it to be fully reproducible afterwards. We have in mind Robert Browning's 'Ah, but a man's reach should exceed his grasp, or what's a heaven for?'}

{From time to time a pupil should be able to say: 'I have seen that done, I have followed it through, understanding it as far as I could. It was worth the time and trouble for the experience of knowing that scientists can do this, and of feeling that, for the moment, I was with them.' We do not expect a young pupil to put it in that emotional way—yet that is the general conviction that we hope he will keep.}

{Most experienced teachers say that it is impossible to teach kinetic theory of gases to pupils at the stage of Year 4 with any derivation of the formula. Most experienced teachers say that it is possible to teach anything provided one takes enough time.}

{The first statement probably refers to teaching schemes in which the pupil is expected to reproduce the material in examinations. Here, where we want the pupil to make the work part of his general experience, we do not aim at facility in repeating the calculation in examinations: we believe in a more general understanding and we take assurance from the second statement that this can be achieved.}

{Of course the second statement has a concealed condition, that the time needed goes up out of all proportion when teaching younger children. On the other hand 'where there is a will there is a way' applies in this matter to both children and teachers. If only we can build up a *wish* to guess the size of a single molecule or atom, we shall find pupils anxious to accept rough methods and special schemes instead of being suspicious of them.}

This deserves some skilful advertising, the teacher somehow placing an intellectual temptation before his pupils. If pupils have been taken once through the argument and seen what a wonderful result can emerge, many of them will be quite anxious to see it once more, particularly when assured that this is *not* something that has to be copied out in an examination, but something to be done for the sake of their own power of knowledge. The second time through will build it into knowledge of something seen with a sense of understanding.}

INTRODUCTION TO QUANTITATIVE KINETIC THEORY

We have discussed the qualitative picture. Pupils have seen models and looked again at the Brownian Motion.

Now we offer a new serious study: the derivation of 'new knowledge' from our theory.

A choice of versions We offer below three suggested versions of the essential argument. We hope that teachers will look at all three and make their own choice for their particular group of pupils. The first two simple versions follow in this chapter. The more professional version is in the next chapter.

But whichever treatment is chosen, we should first show again Demonstration 67, as a model of a rain of molecules arriving at a surface and making a 'fairly constant' force by their bombardment.

1. SIMPLEST VERSION OF KINETIC THEORY: PREDICTING BOYLE'S LAW

The simplest kinetic theory story was suggested in Year 3: we imagine that molecules exist, and are in motion, and we suppose that the pressure of a gas on the walls of a box is produced by the impact of bombarding molecules. We pretend we employ a microscopic demon to put more molecules into the box one by one through a trap door. When he has put in so many that there are twice as many molecules as before, what pressure would pupils expect? There are twice as many molecules to bombard the walls and therefore we should expect double pressure. (See *Pupils' Text 3* or *4*.)

The argument Instead of making a gas of double density by having the demon put more molecules into the same box, we could push a piston in until the volume is halved, and then we have the double density without needing any extra molecules. Then the pressure on the walls should be the same as if we had the full box and had added more molecules (because the walls can hardly know what is near them except a gas of double density). So we now conclude that when we halve the volume we should expect double pressure: we expect Boyle's Law, and are delighted to find it.

Boyle's Law For many pupils the Law is not shown clearly and simply by the traditional apparatus with columns of mercury, which involves careful discussions of adding the difference of levels to the barometer reading. We recommend instead our large visible demonstration.

The simple Nuffield apparatus This has the sample of dry air in a wide glass tube with a coarse scale of volume beside it. The sample is compressed by driving up the tube a piston of oil from a reservoir.

There is an air space above the oil in the reservoir and the pressure is increased by pumping more air into that space with a foot pump. The pressure at the reservoir is measured on a Bourdon gauge which must be graduated to read *absolute* pressure for the sake of clear teaching.

{The essence of this argument is the concealed assumption that gas molecules do not interact—except for a negligible fraction of the time, during collisions. This is the important information about real gas molecules that Boyle's Law gives us when we compare experiment with theory.}

{With more neighbours to collide with, an individual molecule will not travel as far before it makes a collision, but in a collision the two molecules that collide and rebound elastically, simply exchange jobs with each other; so we should not expect the more frequent collisions to upset our prediction. We might again give a demonstration of a head-on elastic collision between equal masses: let a moving steel ball hit a stationary one head on. The stationary one takes on the full job of moving ahead. Then repeat the demonstration with both balls moving and making a head-on collision. Whatever their velocities, the balls simply exchange motions.}

{Of course the collisions between real gas molecules are seldom head-on. However, we are discussing and illustrating a simplified picture in which we deal with motion in one dimension.}

{The story of the two cars that meet on a mountain road which is too narrow to allow them to pass is an illustration that helps some pupils to understand this: the solution in an emergency is to exchange cars and drive backwards. If we use this story, we must start by warning pupils that it is only an illustration.}

{After this we must sketch real molecules moving towards each other and just missing each other, and then in another case moving towards each other, hitting and rebounding. Then we can ask the important question about them. Some teachers prefer to show this with two pupils running from side to side of the room, sometimes just missing each other and sometimes colliding and rebounding.}

{**A private note to teachers. Real gases: modifications** We can even speculate about modifications. Suppose the demon goes on packing molecules into the box until there are so many that the molecules themselves reduce the space available for motion appreciably. Then the to and fro motion of bombarding molecules has a shorter path than we would expect from our simple picture of molecules as points. Bombardments will happen a little more often, the pressure will be a little greater than we expect: and that is what we find when we push our Boyle's Law experiment to very small volumes (at high temperatures). Again, if molecules attract each other when they are fairly close—as surface tension shows—we should expect to find mutual attractions pulling the molecules, so to speak, towards a central clump so that they would not press on the walls so much. That effect would decrease the pressure when molecules are crowded close together, and moving slowly, at low temperatures.}

{The usual explanation—that *all* bombarding molecules are slowed by that attraction and therefore exert less pressure—is misleading because it would suggest a cooler layer of gas near the walls. The real mechanism is this: some slowest molecules are *weeded out* by the attraction and never reach the wall. Thus there is a *less dense* layer near the walls, and that exerts a smaller pressure.}

{In real gases we find both these effects at high pressure and small volumes; and we can distinguish them from each other because they change in different ways with temperature. At low temperatures the effects of attraction make themselves felt strongly: gases even liquefy. The effects of size stay much the same.}

† Demonstration 70 Boyle's Law

Apparatus

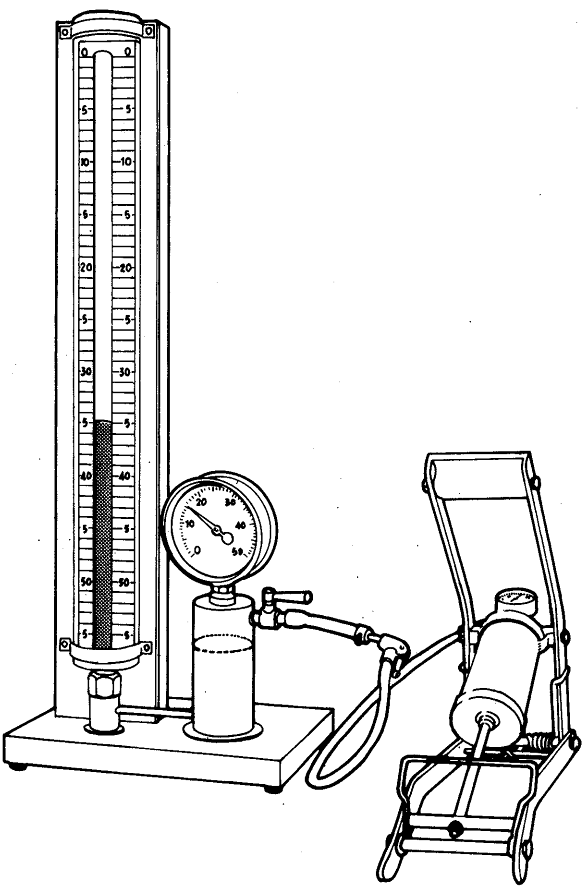
1 Boyle's Law apparatus	item 109
1 foot pump and adaptor	45

Procedure

Apply pressure to the oil in the reservoir by gentle use of the foot pump. Read the Bourdon gauge and the corresponding length of the air column and record them.

Each pupil should try multiplying PRESSURE by VOLUME.

Note: To fill the apparatus with oil, unscrew the Bourdon gauge with a spanner. Fill the reservoir with oil of low vapour pressure. Redex is suitable and clearly visible. It is necessary to tilt the apparatus in the final stage of filling in order to get enough oil into the main tube. When refixing the gauge, tighten the nut enough to get a good seal, but not so much that the thread is damaged.

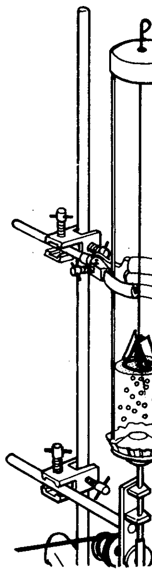


This can be illustrated qualitatively by a model, with the following demonstration.

Qualitative Demonstration 71a Gas model to illustrate Boyle's Law

Apparatus

1 kinetic theory model kit	item 11
1 chinagraph pencil	543
1 fractional horse-power motor	150
1 L.T. variable voltage supply	59
1 retort stand, boss and clamp	503–506
paper or card for loading piston	



Procedure

a. Set up the three-dimensional gas model as already described, but with fewer balls, say three dozen. Insert the paper piston in the tube and make sure it is free to move. Increase the voltage for the driving motor.

Point out the position of the paper piston. This can be marked on the cylinder with a chinagraph pencil.

Pour in more balls to double the number. The piston will float higher in the cylinder.

Add loads of paper or card to bring the piston back to its original position—thus showing the greater pressure exerted by the larger 'density' of balls.

b. As a separate demonstration, keep the number of balls unchanged, but add paper or card loads to the piston. The piston sinks—thus showing that as the pressure increases the volume decreases.

Let pupils return to the marbles in a tray to look at the 'pressure' with more marbles.

Class Expt 71b Crowding marbles in a tray: another illustration of Boyle's Law

Apparatus

1 two-dimensional kinetic model kit	item 12
8 short rulers	

Procedure

Pupils follow these instructions:

* * * * *

a. First agitate the tray of marbles in the usual way. Then put a ruler across it to reduce the area occupied by the marbles. It is easy to hold the ruler still if you put a small book in the tray and hold the ruler firmly up against it.

What is the effect of reducing the area further still? Listen to the collisions with the walls.

b. Borrow some more marbles and add them to see how a 'compressed gas' behaves.

* * * * *

2. SIMPLE CALCULATION OF VELOCITY, WITHOUT ALGEBRAIC DERIVATION OF $PV = \frac{1}{3}Nmv^2$

(This is a strange method that will seem unpleasantly artificial to some teachers, an interesting simplification to others. If the teacher himself reads this method and does not like it, he should probably avoid it. On the other hand, some teachers who have tried it have been pleased to find that pupils of medium ability understand it well enough to enjoy the result, where a longer method would have been too hard.)

We make a crude estimate of the speed of air molecules by a thought experiment that continues a suggestion made in Year 1. Now, in Year 4, pupils have the knowledge needed to finish the calculation.

We tell a fanciful story, but it leads to a sensible answer. We suggest that teachers should try this if they do not intend to try the full derivation of $PV = \frac{1}{3}Nmv^2$—and the ensuing calculation of average speed—with their class. Here it is:

Explain that we are going to make a rough guess at the speed of the air molecules which make air pressure by bouncing on every surface. Remind pupils that we live at the bottom of an 'ocean of air'.

The first measurement: pressure due to the real 'ocean of air' above us. Set up a mercury barometer and measure the height of the mercury column, (about $\frac{3}{4}$ metre).

Demonstration 72 Barometer

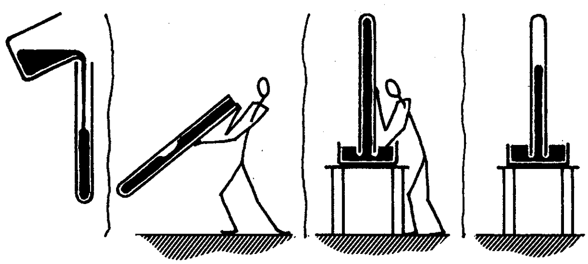
Apparatus

1 barometer tube	item 6I
1 trough	6K
1 metre rule	501
1 mercury tray	524
1 translucent screen	46/1
1 retort stand, boss and clamp	503–504
1 lamp for translucent screen	46/2
mercury (2 kg)	535

Procedure

a. Fill the barometer tube with mercury while pupils watch. Hold the tube over a mercury tray throughout.

The best teaching technique is to fill the tube nearly full, all but a centimetre or two at the open end; close this end with a firm finger; then hold the tube nearly horizontal so that the large air bubble runs *very slowly* to the other end of the tube and back again; it will collect up small sticking bubbles on the way. Then hold the tube upright and fill it to the top.



Hold a finger on the open top of the full tube and invert into the trough of mercury. Keep the finger there until the end of the tube is well below the surface. Pupils should watch all this carefully. Warn them before removing the finger.

This method requires care to avoid mercury hazards.

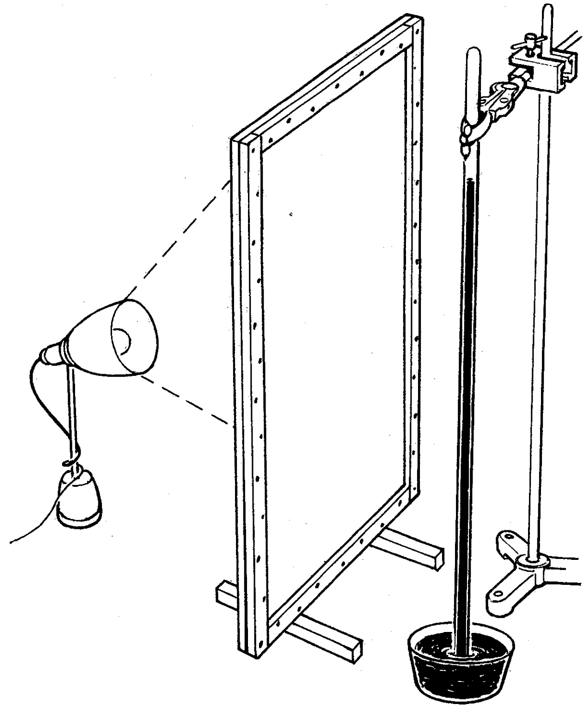
Carry out the whole experiment in front of the translucent screen with a lamp behind so that it is clearly visible to the class, in silhouette against the bright background. Although this is more trouble to arrange than simple lighting from the front, it makes the demonstration far clearer.

Pupils come to the barometer one by one, or in pairs at most, to measure the column height.

This is too important a measurement to be left as a demonstration to be seen remotely.

b. As an alternative, or as an optional addition, use a tall tube (1 metre) open at *both* ends. Dip the lower end in a trough of mercury and connect a motor-driven vacuum pump to the upper end by pressure tubing, *and a mercury trap.*

Silhouette the experiment by placing it in front of a translucent screen with a lamp behind.

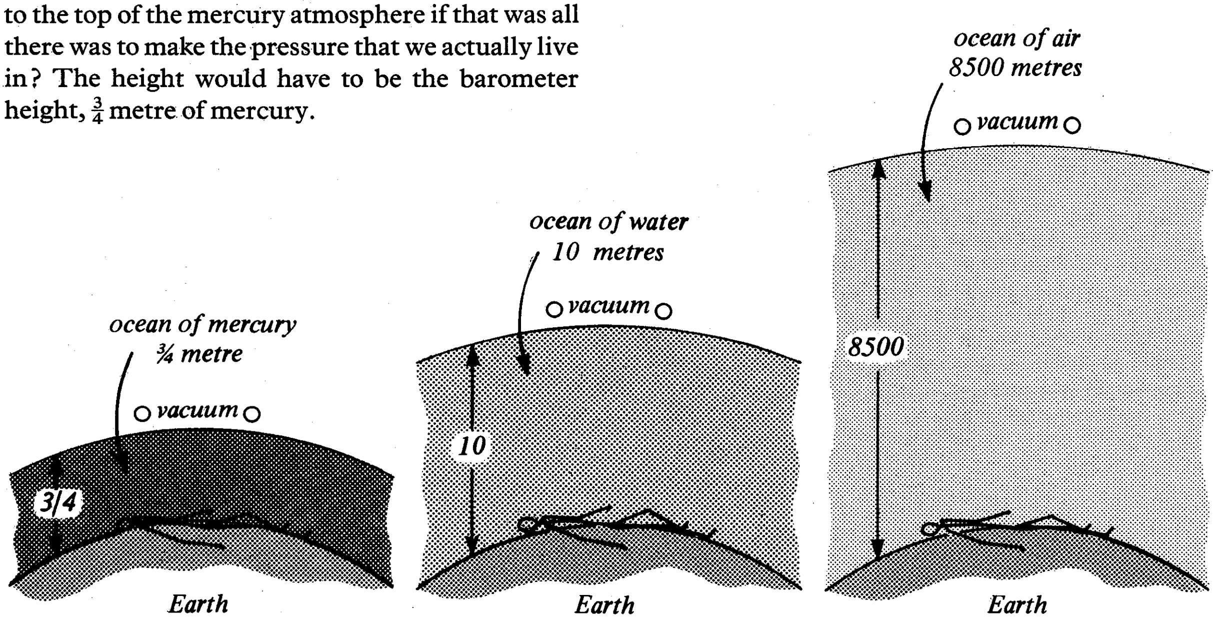


The story Then say to pupils, much as in *Pupils' Text:*

*   *   *   *   *

The air pressure on the mercury outside in the bowl pushes the mercury up inside the barometer. The column of mercury just balances the air pressure. Suppose, just for fun, that we lived under an atmosphere of mercury instead of air. There would be nothing above that—just vacuum. How high would the mercury have to be from the floor to the top of the mercury atmosphere if that was all there was to make the pressure that we actually live in? The height would have to be the barometer height, $\frac{3}{4}$ metre 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 at the top with nothing more above? How high would *that* atmosphere of air have to be to make the pressure we measure here?



An atmosphere of *mercury* would have to be $\frac{3}{4}$ metre high, 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).

How high would a *water* atmosphere have to be?

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

Remind pupils that the real atmosphere gets thinner and thinner as we go higher and higher. (We might show the demonstration model again.)

So the story we are telling is an artificial, simplified one* in order to arrive at an interesting guess. 'Desperate measures for desperate needs.' In fact, some teachers call this 'desperate physics'—a name that proves palatable and helpful to pupils.

The story continued We continue the comparison of the 'oceans' here. The necessary intervening experiments (73A and B, 74, 74X and an optional repetition, 75) are described on pages 19 and 20.

They will show that mercury is about $13\frac{1}{2}$ times as dense as water and 11 300 times as dense as air in the room.

Comparing the 'oceans' Then say:

* * * * *

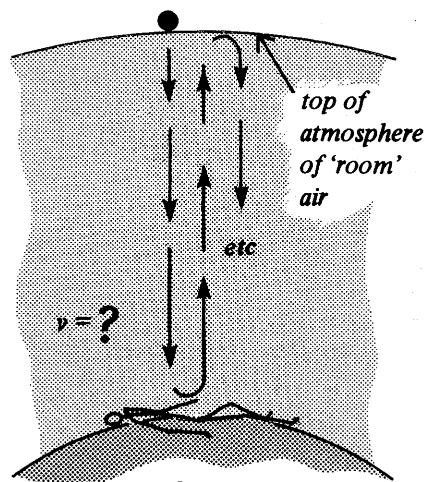
Remember: mercury is much denser than water. In fact, it is $13\frac{1}{2}$ times as dense as water; so a water atmosphere would have to be $13\frac{1}{2}$ times as high as the mercury height, $13\frac{1}{2} \times \frac{3}{4}$ metre, very close to 10 metres.

Our measurements show that mercury is about 11 300 times as dense as air in this room. Then if we had a uniform atmosphere of air, its height would have to be

$$11\,300 \times \tfrac{3}{4} \text{ metre or about } 8\,500 \text{ metres.}$$

Suppose the 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, at rest, starts to fall, faster and faster and faster—like anything else that falls. It does 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. It will be moving very fast indeed when it reaches the ground and bounces against the floor, or the top of your shoe, or anything like that. No wonder air molecules make a big pressure.

Pretend that molecules do fall down from the 'top of the atmosphere' like that. They bounce on the floor or on us, and rebound, losing no energy, up to the top of the atmosphere. They come to a stop there; fall down again and so on.* This is a very rough-and-ready model of what does happen in the atmosphere, but it may help us to make a guess at the speed.



How fast will a molecule be moving if it has fallen from the height that we have just worked out? (Suppose we worked out 8 500 metres.)

The molecule will fall with acceleration g. Starting from rest and falling 8 500 metres, the *time* it takes will be given by $s = \frac{1}{2}at^2$, so that

$$t^2 = 2s\,a = 2 \times 8500/9.8$$
$$= \text{about } 1\,700.$$
$$\text{Then } t = \text{about } 41 \text{ seconds.}$$

* Teachers may need to discuss the importance of rough estimates with pupils. Suggestions are given at the end of each volume of *Pupils' Text*.

* We are assuming that model molecules are perfectly elastic as are real air molecules. We are assuming that they fall all the way without collisions: we are pretending they are infinitely small in size, but that does not change simple kinetic theory much. We are confining the motion to one direction, the vertical: that is artificial and we should admit the defect.

Falling from rest for that time, gaining 9.8 metres/sec in each second, the molecule would reach a speed of 41×9.8 or 400 metre/second.

* * * * *

The expected result is 20% below the proper average value, but we welcome it as a rough guess, made by a risky, imaginative, method.

A demonstration with visible bromine vapour spreading in a vacuum shows that gas molecules do move very fast. That is essential at this point. See the demonstration in Chapter 7.

If a critical colleague tells us that it is not only imaginative but wrong, we should tell him that this method was used by Boltzmann to arrive at the Maxwell distribution, with a modification of the 'uniform atmosphere' assumption. This is the children's version of a famous adult method.

{Nevertheless, our modification is impossible, unless we admit to an unrealistic temperature-gradient. An isothermal atmosphere of uniform density *could not* be in equilibrium—in imagination, apply Archimedes' principles to a sample and see the whole sample fall to the ground!}

THE EXPERIMENTS

We weigh samples to compare air with water and water with mercury.

For air, we use the standard method of weighing a 1 or 2-litre flask before and after pumping the air out. Then we let water in to fill the volume occupied by the air removed.

Demonstration 73 (Method A)
Measurement of the density of air

Apparatus

1 1-litre round-bottomed flask‡	item 234/1
1 bung and glass tube	
1 Hoffmann clip	10V
1 vacuum pump	13
1 chemical balance (borrowed from Chemistry)	
1 trough of water	532
1 measuring cylinder	518/2
pressure tubing	563

‡ A 2-litre flask would be better still: a $\frac{1}{2}$-litre flask should *not* be used.

Procedure

For this experiment borrow a chemical balance from the Chemistry department.

The flask must be the round-bottomed type for safety. Weigh it, complete with bung and a short piece of pressure tubing and clip. Connect it to the vacuum pump and exhaust it. Then reweigh.

To find the volume of air extracted, open the flask under water. The volume of air extracted is the volume of water which enters the flask. Measure this volume, using a 1000 cm^3 measuring cylinder.

Then we could calculate the density. (About 1.2 kg per metre^3 for air at room temperature.) But we seek the densities of air, water and mercury more by habit than by necessity. (Density is a dull unfamiliar concept for many pupils; and there may be confusion over units.) All we need in this chapter is a *comparison* of air with mercury—using water as an intermediary—so that we can change from a $\frac{3}{4}$-metre column of mercury to a column of air (like the air in the room) that makes the same pressure.

Instead of working out the density of air, simply weigh the water that replaces the pumped-out air and calculate the ratio of the weighings: mass of water/mass of air. For a 1-litre flask pumped out well, the result will be about 1000 grams/1.2 grams.

Compare mercury with water by weighing sample bottles. Calculate mass of mercury/mass of water. Result, about 13.6/1.

For the comparison of 'oceans' we should have

MERCURY	WATER	AIR
$\frac{3}{4}$ metre	$\frac{3}{4}\text{ metre} \times \frac{13.6}{1}$	$\frac{3}{4}\text{ metre} \times \frac{13.6}{1} \times \frac{1000}{1.2}$

Alternative method A rough scheme was suggested for Year 1, so that the weighing could be done on a simple balance. That is described below in case teachers prefer it; but we do not advise buying the equipment specially now. At this stage we prefer a more precise weighing; and a chemical balance should no longer be confusing. So we advocate Method A.

Demonstration 73 (Method B) Alternative method for rough measurement of the density of air

Apparatus

1 plastic container with tap	item 10E
1 foot pump with gauge	45
1 rectangular perspex box (10 cm × 10 cm × 10 cm) ‡	10D
1 kitchen balance ‡‡	206
1 large trough of water	532
rubber tube (1 metre)	562

‡ We now recommend perspex boxes 10 cm × 10 cm × 10 cm which are much less expensive, for use in Year 1. If these are bought, it will be easier to have *several* boxes inverted and filled with water ready for use.

‡‡ We now recommend a *kitchen balance. The lever-arm balance*, item 42, previously suggested, is also suitable, provided the container is hung on a long thread from the balance. (If the container is placed on the pan the reading changes significantly when the container is shifted on the pan.)

Procedure

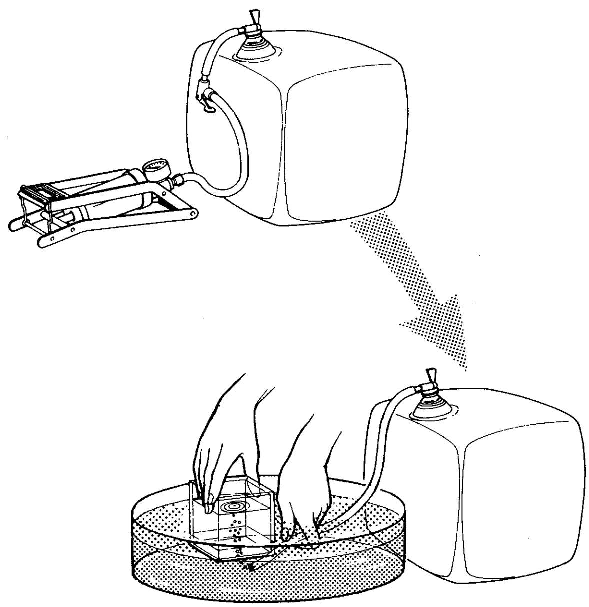
Attach a metre of rubber tubing to the outlet of the plastic container. Weigh the whole on the kitchen balance, the air inside being at atmospheric pressure.

Then pump air *into* the container with the foot pump. The more air that can be got inside the better. Close the tap on the container. Weigh again.

Immerse a rectangular perspex box, full of water, in a large trough of water with the open face downwards. Put the rubber tube in the water with its end well under the inverted box. Open the tap until the perspex box is filled with excess air to a height of 10 cm. Close the tap. Re-fill the box with water. Repeat the process several times until no more excess air comes out.

Each time 1000 cm^3 of air are released to fill the box. Estimate the last fractional filling.

This gives the volume at atmospheric pressure of the 'extra air' that was pumped in. The



weighings give the mass. Calculate the density of that extra air.

With the containers recommended, a difference of at least 8 to 10 grams or more is possible and such a difference can be seen on the balance. The containers will withstand at least 10 grams of air being pumped into them. Tests show that they may burst at *excess* pressure about 0.7×10^5 N/m^2 (10 psi), but without danger to spectators. In some cases the tap blew out at lower pressures, but it is easily replaced.

Experiment 74 Quick comparison of the densities of water and mercury

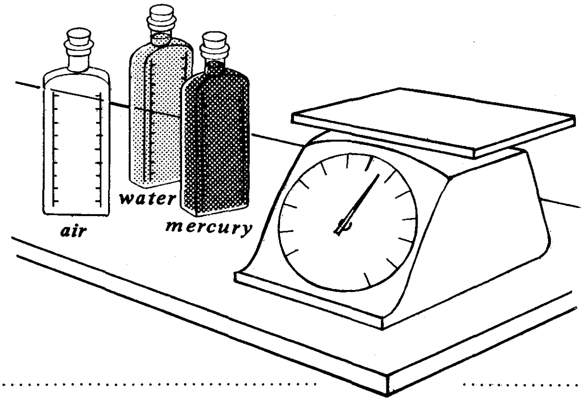
Apparatus

3 equal medicine bottles	items 534
1 demonstration spring-balance (5 kg)	20
a supply of mercury (2 kg)	535

Procedure

To compare (roughly) the densities of mercury and water use three equal bottles, carefully sealed. Medicine bottles are suitable. Weigh the bottles on a domestic balance: one full of air, one full of water, one full of mercury.

If possible leave these bottles on the side, on a felt mat in a tray, so that pupils can lift them for themselves to feel the contrast. If so, each should be closed by a firm cork held in by wire.



Demonstration 74X Density of water *(OPTIONAL NOW)*

Apparatus

1 perspex box (10 cm × 10 cm × 10 (or 11) cm)	item 10D
1 domestic balance (kg)	20
1 cardboard metre cube ‡	223
1 metre rule	501

‡ The demonstration metre cube can be made out of cardboard. It should be collapsible, for storage.

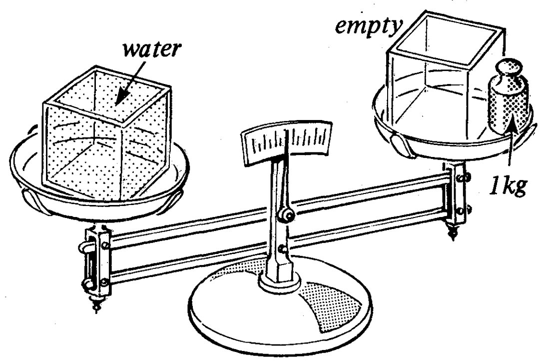
Procedure

Weigh the perspex box empty, on the domestic balance. Fill it with water to a depth of 10 cm and weigh again.

Place the cardboard metre cube beside the perspex box.

Calculate, with pupils, the density of water in SI units.

Counterpoise method



Pupils who are used to saying the density of water is 1 may find it difficult to remember that the density of water is 1000 kilograms per cubic metre. This comparison of a metre cube and a decimetre cube should convince them that it cannot be 1 kilogram per cubic metre.

Demonstration 75 Model showing thinner atmosphere higher up *(REPETITION)*

Procedure

Set up the three-dimensional kinetic model as in Expt. 68a.

Remove the cardboard piston so that the small balls can rise freely up the perspex tube. Pupils look at the thinning of the 'atmosphere' with height.

THE NEXT CHAPTER

Chapter 7 has the essential demonstration of visible bromine vapour spreading in a vacuum, showing that gas molecules move very fast.

Formal derivation of $PV = \frac{1}{3}Nmv^2$ With faster pupils, we hope teachers will try the formal method described in Chapter 7.

CHAPTER 7

GASES II RICHER PREDICTIONS

Molecular theory and its predictions: molecules' speeds; diffusion; a suggestion of Boyle's Law and support from speed of sound

METHOD 3: FORMAL DERIVATION OF $PV = \frac{1}{3}Nmv^2$ (see Pupils' Text)

Important experiments are given in the previous chapter to illustrate Methods 1 and 2. If Method 3 is used, the following should certainly be shown:

† DEMONSTRATION 67 Pressure exerted by a stream of balls

† DEMONSTRATION 70 Boyle's Law

QUALITATIVE DEMONSTRATION 71 Gas model used to illustrate Boyle's Law

† DEMONSTRATION 72 Barometer

† DEMONSTRATION 73A Measurement of the density of air, or

† DEMONSTRATION 73B Alternative method for rough measurement of the density of air

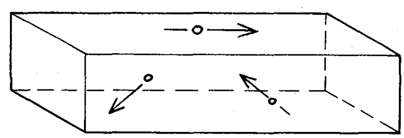
† DEMONSTRATION 74 Quick comparison of the densities of water and mercury

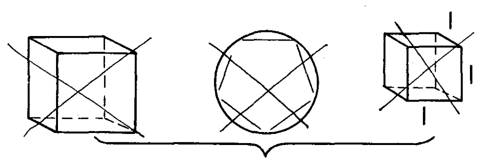
† DEMONSTRATION 74X Density of water

† DEMONSTRATION 75 Model showing thinner atmosphere higher up

Choosing conditions that look honest to beginners In deriving the kinetic theory expression for pressure, we should avoid using specially simplified conditions as far as possible.

We should use a *rectangular* box, rather than a *cubical* one, so that it is easy to distinguish the length along which a specimen molecule travels from the width and height of the end face which that molecule bombards.





misleading or 'too special'

We should also avoid the delightfully ingenious but artificial scheme of picturing molecules in a spherical container in which a given molecule is said to pursue chord after chord of constant size around the interior—even a more realistic version of that scheme would seem oddly artificial to the beginner.

Above all, we should not use a cube of side 1 cm or 1 metre—then the value 1 becomes submerged and invisible. Just as we do not want pupils to think that Newton's Laws only apply to motion where there is no friction, we do not want them to think that the kinetic theory of gases is limited to a gas in a unit cube.

Making the difficult job worth while 'A thing that is worth doing is worth doing well' and for those who can manage it this kinetic theory derivation will be rewarding. The argument is long but it will stay there in *Pupils' Text* to be looked at for reminders.

The only really difficult part of it is the use of rate-of-change-of-momentum to measure the force. To get over that difficulty, we should take two precautions:

Precaution 1 Give a general description *beforehand* of what we are going to do—preferably a day or even a week beforehand.

Precaution 2 Carry pupils through some preliminary exercises: Problems A, B, . . . of Question 4 in *Pupils' Text*. Explain clearly this is preparation for success in a difficult job to come.

Both of these 'precautions' are set forth fully in *Pupils' Text*. Here are some private notes to teachers about them.

{**Note 1 Elastic collisions** For pupils, we assume that the molecules are elastic; that is, they do not lose kinetic energy in collisions. Of course, gas molecules *can* collide inelastically, with a disappearance of some K.E., though they have to be enormously more energetic than gas molecules at room temperature. In an *inelastic* collision a molecule may be torn apart into separate atoms, or a molecule may be raised to an excited state, or an electron may be knocked completely out of an atom or molecule, leaving it ionized; or there may be a loss of energy by radiation.}

{All these are hopelessly improbable events among molecules of gases at ordinary temperatures as we know them. The *average* K.E. of an air molecule at room temperature is about $\frac{1}{30}$ electron·volt. A photon of green light has about 2 electron·volts. To ionize most kinds of atom costs a dozen or more electron·volts. Gas molecules at room temperature bounce against each other with perfect elasticity.}

{And, of course, such collisions cannot 'manufacture heat by friction'—an entirely mistaken idea that some pupils conceive. The heat-energy of a gas is there in its molecular motion, and if in a collision a gas did lose some motion and generate heat, that would mean it was losing some of its motion and thereby increasing some of its motion—a paradox.}

{However, molecules with more than one atom can have energy of rotation and energy of vibration which could be exchanged with K.E. of straightforward motion when they collide. In this way some collisions may be less than elastic as regards straightforward K.E., and others correspondingly superelastic, but the vast collection of molecules in any ordinary sample will maintain an *average* that fits perfect elasticity. So we certainly should not worry pupils with any doubt—or even discussion of this.}

{**Note 2 Praise of theory** As we finish looking ahead in 'Precaution 1', we say in *Pupils' Text*, 'This is theory: the thinking that scientists do tells them . . .' In the earlier edition of *Teachers' Guide IV* we said '. . . that *clever* scientists do . . .'—thinking, on behalf of pupils, of Drinkwater's chorus in *Abraham Lincoln* saying 'And when we worship greatness passing by, ourselves are great.' We suggested that description because the making of good theory *is* clever work. The kinetic theory was made by great men.}

{However we do not suggest *clever* as the necessary word to use with all pupils: each teacher will need to make a choice to fit the interests or vocabulary of the class. In some cases, a phrase like 'clever scientists' is irritating; and the idea should be put differently. Some commentary is needed in building up an understanding attitude to theory, but the proper choice of wording depends on the tastes of the teacher and the class.}

{**Note 3 Examinations** We make it clear that this formal derivation should not be learnt by heart in preparation for any O-Level examination. An acquaintance with it might be useful; but the formula $PV = \frac{1}{3}$ . . . would be printed on the question paper.}

{**Note 4 A short cut to be avoided** When a stream of particles hits a wall we calculate the force by using $F \times t =$ change of mv. Professional physicists proceed at once to calculate the momentum-change *per second*; but for beginners that imposes a jump which is strange and unnecessarily sudden. Using an interval of 10 seconds makes it easier to see that they are using FORCE × TIME = change of MOMENTUM. Of course the chosen period of time soon cancels out.}

{**Note 5 Equal pressure on all walls** It is obvious to us that the predicted pressure is the same on all walls of the box. But some pupils find it satisfying to see the algebra calculation of pressure repeated for another face of the box, of area *ab* instead of *bc*.}

THE OUTCOME $PV = \frac{1}{3}Nmv^2$

{This prediction is produced by logic (algebra) from our assumptions that molecules exist, that they are tiny, numerous, elastic; that they are in rapid motion and that they produce gas pressure by their bombardment. We further assume that in gases they exert negligible forces on each other except briefly in collisions and that their motions and effects are described by Newton's Laws.}

{Although some of these assumptions which went into the logic-machinery are vouched for, or at least supported by, experimental knowledge, we pursue a long tale to produce $PV = \frac{1}{3}Nmv^2$ and unless this theory is fruitful in return it will seem top-heavy—a wrangling game rather than a web of knowledge. We hope our young pupils will see a stronger imaginative picture to co-ordinate knowledge and provide a vocabulary for discussion and prediction. But unless at least one prediction is developed a critical student should be disappointed.}

Therefore we must not be content to produce $PV = \frac{1}{3}Nmv^2$ with a flourishing gesture of success and leave kinetic theory at that. We must as a duty to the good name of science derive predictions and interpretations from it. In this chapter we offer:

1. a prediction of Boyle's Law. This comes with a doubt: we cannot safely predict PV = constant at constant temperature unless we know that the speed of molecules is independent of density—and we make a rough appeal to the speed of sound to support that.

2. an estimate of average speed of air molecules. We assumed great speed. Now we can say *if* our assumptions fit Nature. We can calculate the speed of these hypothetical particles: about 500 metres per second. We must do this for all pupils—either by the rough method of Chapter 6 or by using the formula we have derived here. To leave our tower of theory with a shaky hint of Boyle's Law as its only outcome would be an educational crime.

3. a comparison of molecular speeds for different gases, and then we could predict and discuss diffusion with application to other sciences and an essential use in separation of fissionable uranium.

4. a measurement of volume-change from liquid to gas lets us estimate the spacing of gas molecules—far apart, out of each other's influence. And then we can even go back on that last assurance and use our theory to predict the effects of small attractions.

5. with further speculation, estimates of the spacing, mean free path and the actual size of our hypothetical air molecules. That is done in Chapter 8.

BOYLE'S LAW?

We can point out that $PV = \frac{1}{3}Nmv^2$ predicts or suggests Boyle's Law *providing we have some assurance that molecules keep the same speed,* at the same temperature, even when crowded closer together. Many an honest physicist would say that at this stage of the discussion he does *not* have any such assurance; so we should *not* make a tremendous celebration about arriving at Boyle's Law. Instead we should go straight on to a remarkable estimate: the speed of air molecules.

Yet we should comment on the relation of our result to Boyle's Law and unless pupils have recently seen a clear demonstration of Boyle's Law, we should show it now.

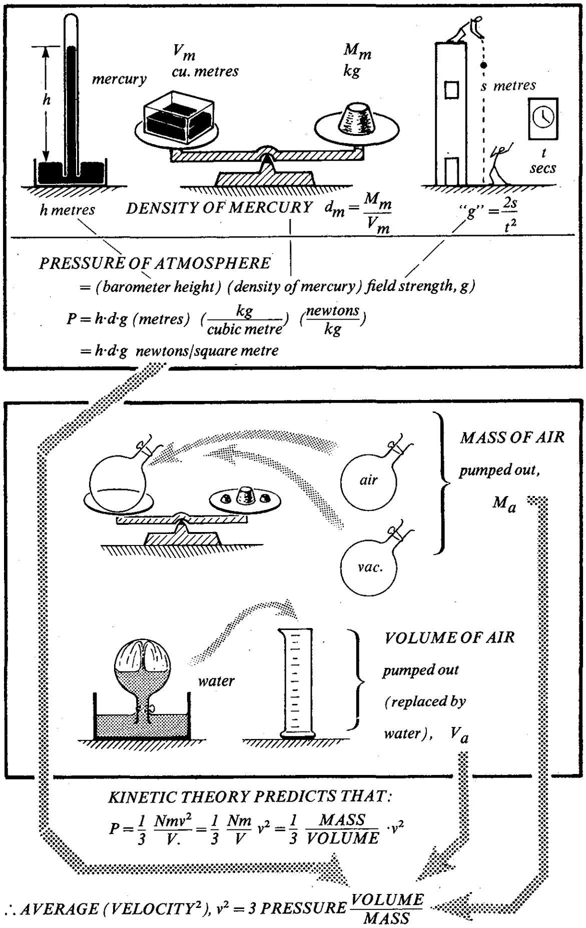
And we can provide indirect assurance that molecular speeds are independent of pressure (provided the temperature stays the same) by a demonstration that is somewhat difficult but quite impressive. That is a measurement with an oscilloscope of the speed of sound with the pressure changed from 1 atmosphere to $\frac{3}{4}$ to $\frac{1}{2}$ atmosphere.

Pupils see no change of speed and make an inference about air molecules from that.

See Demonstration 82, Speed of sound, later in this chapter.

SPEED OF AIR MOLECULES

Point out to pupils that if they trust the expression they have arrived at, $PV = \frac{1}{3}Nmv^2$, they can calculate the speed of molecules from simple measurements. In that way our theory will produce a piece of information about one of its assumptions. We *assumed* that gas molecules are small, numerous, *speedy*, elastic, and make the pressure by their impacts on the walls. Now, we can calculate the speed with which we must endow them. We can take a measured sample of gas, and knowing P the pressure, V the volume, $\frac{1}{3}$, and Nm (which is the total mass of gas in that volume), we can calculate v^2, and thence an average speed.



Pressure Set up a mercury barometer and discuss the measurement of atmospheric pressure all over again. See Demonstration 72. In our earlier demonstration we expressed the pressure in metres of mercury. Explain to pupils that we must now measure pressure in newtons on each square metre because we have been predicting gas pressure with the help of Newton's Law II using

FORCE × TIME = CHANGE OF MOMENTUM.

Therefore the force must be in units that fit in $F = ma$. Since we use kilograms and metres/second per second the force will be in newtons and the pressure in newtons per square metre.

Density We need the mass of a measured volume of air. (There is no need to drag in a formal description of density here. We should measure it by measuring a mass and a volume and we might as well just use those two separate measurements now.)

Either use the traditional method of pumping out a 1-litre or 2-litre flask and weighing it full of air and empty, or return to the method of Year 1.

The traditional method of Demonstration 73A requires a special balance and would have to be done as a demonstration experiment. Some pupils will enjoy returning to the method of Year 1 and repeating it as a class experiment now that they are going to make an important use of it. See Demonstration 73B.

Measurements show that 1 litre (0.001 metre^3) of air weighs 1.2 grams (0.0012 kg), so 1 cubic metre weighs 1.2 kilograms.

Then pupils calculate v from $PV = \frac{1}{3}\ Mv^2$. With these data pupils will find that the speed of air molecules is about 500 metres/second (1800 kilometres/hour). This is an astounding result—over 1000 miles/hour—faster than a small rifle bullet.

If pupils have arrived at that with some of their own measurements they will not only be astounded by its size but they will be impressed with it as an 'atomic' measurement that they have made.

An incredible speed. What has gone wrong? Can air molecules really be travelling as fast as that? Of course atmospheric pressure *is* astonishingly high—think of all those pressure demonstrations in Year 1. In fact, air molecules *are* travelling at that kind of speed. Of course, some are travelling faster than that and others slower just as in a large group of people some are richer than average and some are poorer than average; but—unlike rich and poor, who often stay like that—a gas molecule that is moving slowly now may be moving much faster than average after the next collision and a faster one may be slowed down.

The reason why gas molecules have a great variety of speeds is that they are colliding with each other frequently and exchanging kinetic energy in collisions so that a molecule sometimes moves faster and sometimes slower. Of course, the whole lot keep the same total K.E. all the time; therefore (dividing by the number of molecules) they keep the same *average* kinetic energy per molecule all the time.

With a fast group, sketch a histogram or chart showing the velocity-distribution of molecules and marking the average speed near the hump.

Direct test of molecular speed? Tell pupils that it is possible to measure the speed of gas molecules directly; but it is difficult because most molecules are invisible.

Demonstration of high speed of molecules Although we cannot show a direct measurement of air molecules, we can show that gas molecules move very fast if we use some visible molecules: brown bromine vapour.

Bromine molecules are more massive than molecules of oxygen or nitrogen. Their average speed is only 200 metres/second, but still . . .

Fortunately bromine is now obtainable in small sealed capsules or 'ampoules' of glass, which can be smashed inside the apparatus to release bromine. We have devised a scheme that uses these ampoules safely.*

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* In preliminary trials, several members of the Nuffield group devised ingenious schemes for releasing bromine; but each of those schemes involved some risk. Where the bromine is fed in through an open funnel with a tap, it has first to be pipetted from a stock bottle. Although teachers in trials were skilful and had no trouble this is in general a dangerous method: the vapour pressure of bromine is high and rises with slight warming, so there is danger of squirting bromine, or splashing it out, during the pipetting. That method should not be used.

There have been ingenious suggestions for using the ampoules in a plain glass tube with a rubber stopper at each end, the ampoule being smashed inside that tube. That is simple and economical, but we do not believe the economy is worth the risk. Bromine attacks rubber, and to have liquid bromine released in contact with the large rubber stopper at the bottom is courting trouble. The stopper will fit and hold the first time, but we should not trust it after that. Furthermore, there is too much danger of the stopper loosening and releasing some *liquid* bromine.

Therefore we urge schools to use our special design. The main diffusion tube is a closed glass tube with only one opening to the outside world, so that there is no danger of releasing bromine to the pump by mistake.

For further details, see the box.

DIFFUSION OF BROMINE: THE EXPERIMENTS

Bromine diffusion: Description of apparatus, and its care

MAIN TUBE. The diffusion tube is a closed glass tube (40 to 50 cm long, 5 cm diameter) with only one opening to a wide side tube near one end, with a rubber bung.

A glass tube through the bung carries liquid bromine to the main tube, so that only bromine vapour and not liquid comes in contact with the rubber. (Nevertheless, the bung must be replaced by a fresh one unless used again on the same day.)

STOPCOCK AND CAP-TUBE The glass tube that runs through the bung is part of a glass stopcock with large bore—8 mm 'Interkey type'. The stopcock must be large, 8 mm bore and must be spring-held to prevent accidental loosening. Ordinary quality suffices: high vacuum quality is unnecessary.

Including a stopcock in the design—which may seem unnecessary in the case of diffusion in *air*—enables the experimenter to separate the two processes:

(i) Release of bromine by breaking the capsule.
(ii) Admission of bromine to the main tube.

Teachers will find that separation into two stages is both a comfort in manipulating the apparatus and an advantage in showing pupils what is happening.

A short piece of fairly thick-walled rubber tubing connects the other end of the stopcock to a glass 'cap-tube' with a bromine capsule inside.

BROMINE CAPSULE The glass capsules each contain 1 cm^3 of liquid bromine. In teaching, one may say 'like a tiny wine bottle, with a neck which is easily broken to release the liquid'.

CLEANING THE APPARATUS After the experiment put the whole apparatus in a plastic bucket half full of dilute ammonia solution and take the apparatus to pieces under the solution. Plunge the lower end of the apparatus in first, remove the bung from the main tube; then dismantle the stopcock etc. The apparatus can then be washed with ordinary detergent, dried and assembled later.

If the main tube is dirty with tap grease, wash it with acetone.

It is sensible to wear rubber gloves for this cleaning process. Rubber gloves are not necessary during the main experiment. They will not increase the teacher's dexterity and they will invest the experiment with an air of danger which it does not deserve.

DRYING THE TUBE FOR IMMEDIATE RE-USE If the apparatus is to be used for several classes on the same day it will need to be dried quickly after cleaning. The design of a closed tube with only one entry is a safety measure but it makes drying the tube a slow process. Unless spare tubes are available, we recommend a hair dryer to blow hot air into the tube after a final washing with alcohol.

MAINTENANCE Before the apparatus is used, clean the stopcock and put fresh grease on it. Vaseline is better than tap grease (which may contain rubber and become more messy in contact with bromine). Vaseline, like paraffin wax, is inert. Avoid the modern form that has air bubbles in it—which may make the tap leak).

The rubber bung must be replaced by a fresh one when bromine has hardened its face. A bung can be used for several experiments in the course of a few days, but if it is kept longer the rubber will harden and may crack or damage the glass side-tube. Then a new bung must be used. (For economy: soon after using the apparatus slice off the end of the stopper where it has hardened.)

The bung must make good contact with the glass side-tube. To ensure that, moisten it with saliva. On no account use vaseline, or the bung may ooze out of the tube. If the bung seems likely to slip out, wire it in.

The short piece of rubber tube that carries the capsule will be hardened by bromine, and using again is risky. Throw it away after use and install a fresh piece when the experiment is repeated.

Demonstration 76 High speed molecules? Bromine 'gas' diffusing in air

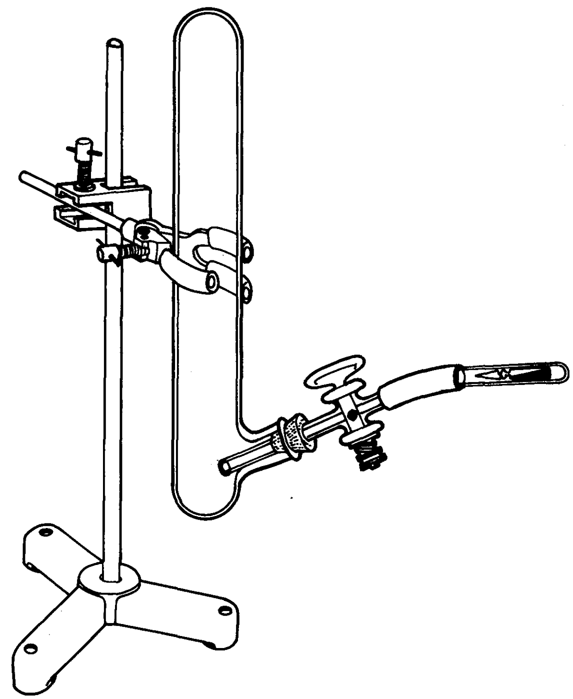
Apparatus

1 bromine diffusion kit	item 8
1 retort stand, boss and clamp	503–506
1 translucent screen	46/1
1 lamp	46/2
pliers	
ammonia solution, $\frac{1}{4}$ strength	
beaker (1000 cm^3) for ammonia	513
plastic bucket	533
(hair dryer for tubes)	

Safety

Bromine is a dangerous substance. If liquid bromine splashes on the skin it makes a bad blister. Bromine vapour will attack the skin and will produce a sore throat if inhaled.

Bromine attacks almost any common material except glass and paraffin wax. Great care should therefore be taken with this important experiment.



However, with the sealed capsules in which the bromine is supplied and the apparatus and procedure that we recommend, it is safe in the teacher's hands. The beaker of ammonia solution should always be at hand, at every stage of preparation and experiment. Then if any bromine escapes it can be treated before it does harm.

Ammonia combines with bromine to form harmless white ammonium bromide. Strong ammonia solution '0.880', diluted to quarter strength, provides an excellent safeguard.

If bromine splashes on table or skin, pour ammonia solution on at once.

Ammonia should not be used near eyes; use plenty of cold water instead.

(Sodium thiosulphate, photographic 'hypo', is sometimes suggested as an alternative to ammonia. We have found it slower and less convenient).

Preparation

(See the suggestions for cleaning, maintenance and drying given in the box.)

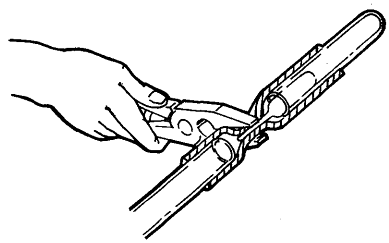
Clamp the main tube firmly in a vertical position in front of the translucent screen. A lamp behind the screen shows the tube silhouetted against a bright background. The bung should already carry the stopcock with its tube pushed nearly all the way through, so that it will deliver liquid bromine to a place just above the bottom of the main tube. Fix the bung in place; and wire it in if necessary.

Procedure

Show a capsule of bromine against the translucent screen (or show it with an overhead projector). Place the capsule in a cap-tube. Hold the cap-tube upright and push a short piece of rubber tubing gently onto it. Push the other end of the rubber tubing onto the outer tube of the stopcock. (The rubber tubing must fit tightly. It should not be too short or there is a danger of pulling it off the glass tube when squeezing it—6 cm is sufficient, 4 cm is too short.)

Keep the stopcock closed. Warn pupils that the capsule is about to be broken. Squeeze the rubber tubing with pliers to break the neck of the capsule. (It is usually easier just to bend the rubber tubing with fingers, though that is not quite so safe). Liquid bromine will run down to the entry of the stopcock. Point to it there. Pupils watch carefully.

Give a signal and turn the stopcock to admit the



bromine to the main tube. Leave it for some time so that pupils can see the diffusion in progress.

Later we shall offer pupils a difficult measurement of bromine's progress through air, with reasoning which will lead from that to an estimate of the size of an air molecule. For now, ask:

'What experiment would you like to see next? Can you suggest an experiment with bromine molecules which might show us their great speed?'

Bromine diffusion in vacuum We expect the suggestion that bromine should be allowed to diffuse in a vacuum. Then we show that, using a duplicate of the apparatus used for diffusion in air.

Demonstration 77 High speed molecules! Bromine diffusing in vacuum

Apparatus

As for diffusion of bromine in air with the addition of:

vacuum pump	item 530
pressure tubing (1 to 2 metres, according to location of pump)	8E
connector to join pressure tubing to wide stopcock tube	
vaseline‡	

‡ The vaseline should be free from air bubbles; the kind frothed-up with air is unsuitable. Modern silicone tap-grease works well but makes the main tube very difficult to clean afterwards.

Preparation

Clamp the main tube firmly. Make sure the stopcock is clean and well greased with vaseline.

Make sure the rubber bung is a fresh one that fits securely and will not let air leak in. Moisten it with saliva to ensure good contact.

Place an opaque white screen behind the apparatus (or a translucent screen with a lamp behind).

Procedure

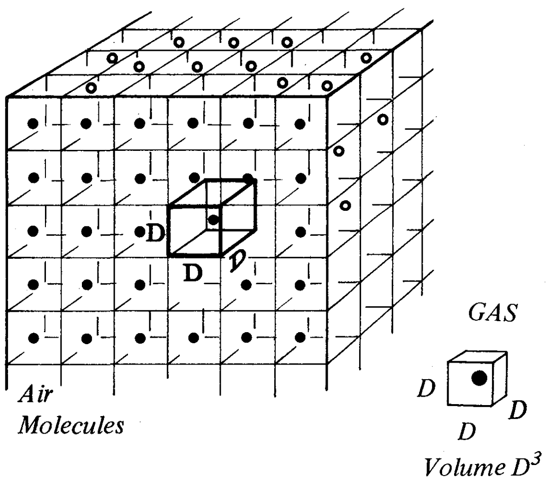
Connect the motor-driven vacuum pump to the stopcock and pump the main tube out to a good vacuum (as indicated by the sound of the pump). Turn the stopcock off. Remove the pressure tubing. Attach the short rubber tube with cap-tube already loaded with a bromine capsule.

Leaving the stopcock closed, break the capsule. Warn pupils to watch carefully. With a count down, open the stopcock quickly.

A FURTHER GUESS ABOUT AIR MOLECULES: HOW FAR APART?

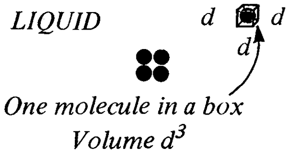
We can say something about the spacing of molecules—their average distance apart in air.

Sketch a 'snapshot' of air molecules on the blackboard, as chalk marks in random disorder. Then reorganise the sketch into a regimented version, an array of cubical cells, each of side D. There is one molecule in each cell. Then the distance of a molecule from each nearest neighbour is also D. D would tell us some kind of 'average spacing-apart' of molecules in common air. The space occupied by one molecule is D^3.



Ask pupils to picture molecules in liquid. There the array must be much smaller, closely crowded, but the molecules are the same size as in gas. They cannot be jammed tightly together, in closest packing, because the material would then behave like a solid. To maintain fluid properties characteristic of a liquid, one molecule must be able to wander among others. And yet liquids are very hard to compress. Also, the molecules must be so close that the forces which we meet in surface tension can hold the liquid together.

As a crude picture that will lead to a rough estimate, pretend that each molecule in the liquid is in a little cubical box of side d, the diameter of a molecule. (Of course, real molecules are not hard lumps like billiard balls, and certainly not spherical: but this is part of our simplifying assumption.)



Sketch molecules in the liquid, enclosed in little cubical boxes, $d \times d \times d$ stacked in a cubical array.

{At a glance, this picture seems to have placed the molecules too close together for liquid behaviour; but the volume of space occupied, d^3 is almost twice the volume of the sphere itself, and such a spacing would have liquid behaviour.}

Suppose that in liquid the spacing between neighbours is d, 1 molecule diameter. How much greater is the spacing in common air? We can find the answer to that if we know the volume-change from liquid air to air. Since that answer would be an interesting piece of information—part of our kinetic-theory picture of gases—we should measure or estimate that volume change if possible.

Volume change We need to measure that ratio of volumes, V_{gas}/V_{liquid}, because that will tell us D^3/d^3 thence D/d; and then we shall know how many molecule diameters air molecules are spaced apart.

So we measure that volume-change for some substance. Liquid air (or rather, liquid nitrogen, would be best—then we should know about molecules of air in the room. But schools find liquid nitrogen expensive and difficult to obtain, although it is a common commodity in university labs. Fortunately the volume-change is much the same (within a factor of 2) for many substances. So a substitute will serve to give a good idea of spacing.

The space occupied by *one* molecule in liquid (according to our picture) is $d \times d \times d$ or d^3. The ratio D^3/d^3 must be the same for every molecule. So it is the same for the whole lot, for all the molecules in a sample:

$$\frac{D^3}{d^3} \text{ is } \frac{\text{volume occupied by one molecule in gas}}{\text{volume occupied by one molecule in liquid}}$$

$$\therefore \frac{D^3}{d^3} = \frac{\text{volume of sample of gas}}{\text{volume of same sample as liquid}}$$

For liquid air or liquid nitrogen, the volume-change to gas at room temperature is about 1:750; for solid CO_2, 1:850; for water to steam at 100°C it is about 1:1650; for petrol at 90°C it is about 1:800.

We suggest using petrol. Although that seems a strange substitute, it provides an easy, dramatic demonstration.

If the school has dry ice available in compact block form, that might be used in an optional addition.

Once pupils have seen a real expansion—petrol—the corresponding value for air (1:750) should be announced.

Spacing of molecules in air Ask pupils what a volume change 1:750 will tell them about the distance apart of air molecules.

Teachers who have tried this with pupils find that the next step seems fairly easy. Pupils themselves suppose that molecules are practically 'in contact' in liquid, one molecule diameter from centre to centre. And when they think of the gas spread out to 750 times that *volume* they jump to the conclusion that average spacing apart in gas is the cube root of 750—namely 9 or 10 molecular diameters. That seems to be a harder piece of reasoning for us than for pupils. But pupils who do find it hard should be given help so that they see clearly that this is a reasonable statement about gas molecules.

Demonstration 78a Change of volume, liquid to gas, using petrol*

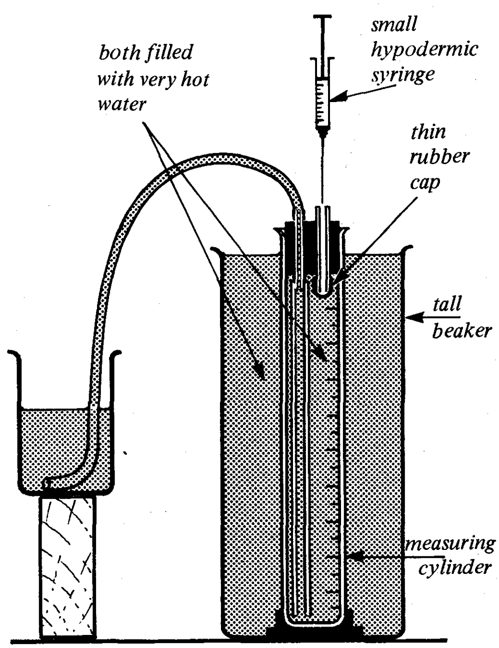
Apparatus

From Change-of-Volume Kit**: item 204	
measuring jar 100 cm^3	204/A
special rubber stopper‡ for measuring jar with 2 tubes inserted	204/B
plastic tube to extend to bottom of measuring jar	204/C
plastic tube to carry over to beaker	204/D
small rubber cap (to be pierced by hypodermic needle)	204/E (= 148/2)
hypodermic syringe 1.0 cm^3	204/F (= 148/3)
2000 cm^3 glass beaker, tall-form	204/G
wire stirrer	204/H
1 beaker, 400 cm^3	512/2
Petrol‡‡	

**New Nuffield item.

‡ If the jar has a pouring lip, the stopper must extend below the lip to prevent leakage there.

‡‡ Ordinary petrol does well. Do not use the fluid from cigarette lighters: its boiling point is too high.



Procedure

Place the measuring cylinder in the tall beaker. Put about 200 cm^3 of water in the small beaker. Fill the tall beaker and the measuring cylinder with hot water (80°C). Close the cylinder with the bung and bring a plastic tube from the outlet in the bung over to the water in the small beaker.

Push the needle of the syringe through the rubber cap on the short tube in the bung. Inject 0.1 cm^3 of petrol. As the petrol expands to vapour the displaced hot water runs over into the small beaker.

To reverse the change, take the measuring cylinder out of the large beaker and stand it on the table. Wait for it to cool to, say, 60°C. (The end of the plastic tube must stay under water in the small beaker.)

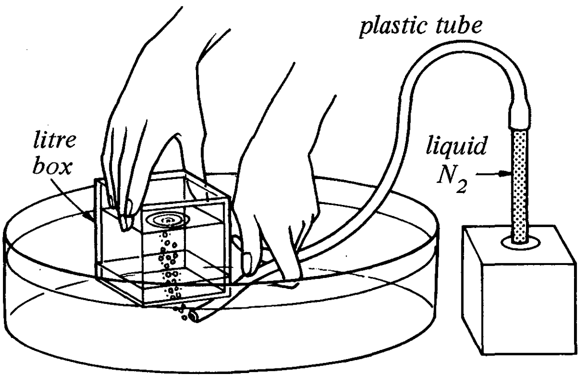
* In the first edition, we suggested a demonstration with a drop of water in a large hypodermic syringe; but that has proved difficult as well as expensive.

Demonstration 78b Change of volume: liquid nitrogen to gas *(SPECIAL OPTIONAL alternative to Expt 78a)*

Apparatus

a supply of liquid nitrogen (or liquid air) is essential for this experiment
1 10-cm^3 measuring cylinder — item 304
2 1000-ml large measuring cylinders — 518/2
  or several perspex boxes,
  10 cm × 10 cm × 10 cm — 210
thermos flask for liquid nitrogen
tank of water
length of plastic tubing to fit small cylinder

Liquid nitrogen can be obtained in suitable quantities, a few litres, from British Oxygen Company depots throughout the British Isles. It is easily transported in ordinary thermos flasks.



Procedure

Hang the small measuring cylinder on a piece of wire and lower it into the vacuum flask of liquid nitrogen (or air). As soon as it has cooled it will fill. Remove it and slip the warmed plastic tubing over its neck. Immerse the other end of the tube in water in a tank so that the gas bubbles out and can be collected in a plastic box (or in an inverted measuring cylinder) previously filled with water.

Once the boiling has started, it is not possible to stop it while one refills a plastic box or a cylinder with water. Therefore it is necessary to have two or more receivers.

The result will be surprising: 5 ml of liquid turns to about 750 times as much gas.

Alternative Demonstration 78c Change of volume: solid CO_2 to gas
(OPTIONAL ALTERNATIVE)

Apparatus

1 1000 cm^3 measuring cylinder — 518/2
block of 'dry ice' — 19/1 and 19/2
bowl of water
Hacksaw

Procedure

Saw a small brick of dense dry ice, say a 2-cm cube, from a block and measure its dimensions quickly.

At once put the 'brick' into water in a bowl and cover it with an inverted measuring jar full of water. Collect the gas and measure its volume.

SPEED OF SOUND AND MOLECULES' SPEED

We suggest looking at the speed of sound in air to support the reasonableness of the large speed that we have predicted for air molecules.

If pupils speculate about the mechanism of a sound wave, in terms of air molecules, they may find they expect sound to travel almost as fast as molecules.

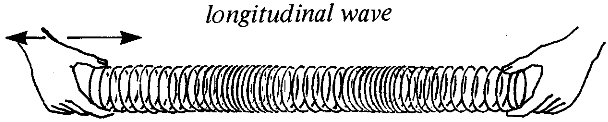
(In fact, the speed of sound in air is about 340 metres/second, while the average molecular speed, according to our prediction, is 500 metres/second. After the following discussion, pupils may consider that reasonable agreement.)

We shall not resume serious studies of waves till Year 5; but we may mention a picture of sound waves. We ask pupils to think of a 'wave' travelling along a line of railway wagons with springy buffers, at rest on a siding. An engine gives the end wagon a sudden push and then leaves it: the 'compression' travels along the line. Some pupils find this easy to picture straightaway, because they have watched shunting operations; others find it easy to picture only after they have drawn sketches of wagons with little connecting springs between them. Remind pupils of a longitudinal wave travelling along a slinky; perhaps show that again.

Demonstration 79 Longitudinal wave along a slinky

Apparatus

1 large slinky	item 101



Procedure

Stretch the long slinky on the floor and send a *longitudinal* pulse along it. It will be reflected at the far end and return along the length.

Demonstration 80 Longitudinal wave along a line of pucks

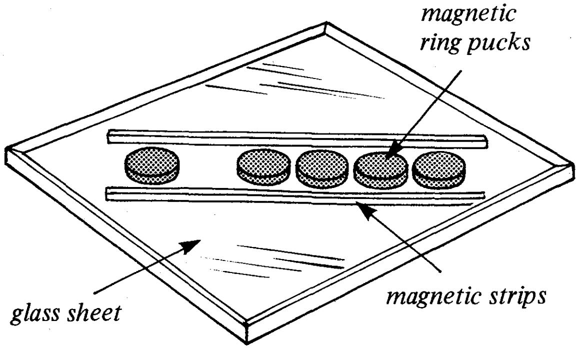
Apparatus

1 Edinburgh CO_2 pucks kit	item 95
4 *additional* large magnetic pucks	169 (= 95C)
1 CO_2 cylinder	19/1
1 dry ice attachment	19/2

Preparation

Set up the mounted glass plate on the floor or a table and level it as usual with wedges. Clean the plate with methylated spirit and polish it.

Stretch two lengths of magnetic strip diagonally across the plate to make an 'avenue' in which the magnetic pucks can move along a line.



Procedure

Obtain solid CO_2 from the CO_2 cylinder and dry ice attachment and place a little under each of the magnetic ring pucks aligned between the magnetic strips. Set the end puck moving towards the others. Pupils watch.

Demonstration 81 Waves along a line of trolleys

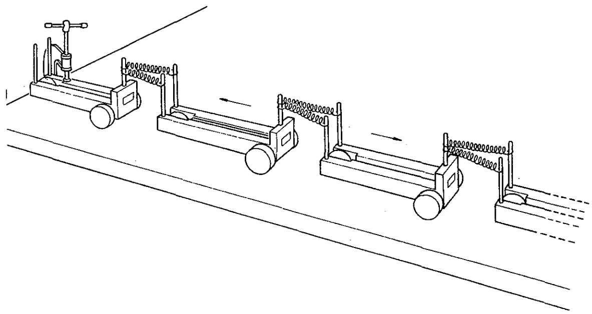
(OPTIONAL)

Apparatus

20 dynamic trolleys	item 106/1
40 expendable springs	2A
60 trolley pegs	565
1 G-clamp	44/1

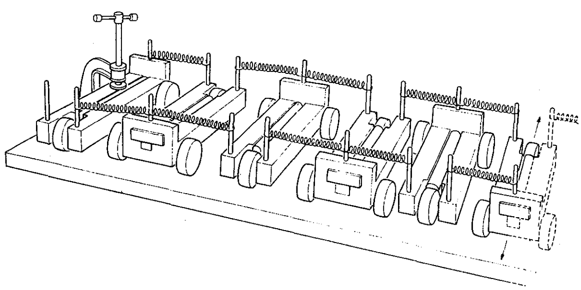
Procedure

a. *For longitudinal waves* A line of dynamics trolleys connected by springs makes a good model.



b. *For transverse waves (unnecessary now)* Clamp a trolley to one end of a smooth bench and connect the others with springs as in the sketch. Space the trolleys apart so that they can move without hitting each other. Give the trolley at the unclamped end a sudden deflection to one side and back to start a pulse wave travelling along the line of trolleys.

Then oscillate the end trolley continuously to show continuous waves. (Unless the bench is very rough reflections from the clamped end are likely to cause standing waves. A cloth on the bench may help.)



Then ask about air molecules. Sketch a line of molecules spaced ten diameters apart and ask how a sound wave could travel along that line, when there are no connecting springs between one molecule and its neighbours. (We know that, because if there *were* long-range springy forces we should not find Boyle's Law holding.)

Illustrate the line of gas molecules by a line of ring-magnet pucks, each with some solid CO_2 under its lid, placed on a glass table with side walls to limit the motion to a straight roadway. Place the pucks some distance apart, then start a 'wave' by pushing the end puck so that it crowds the next few pucks. Or do the same thing with a long train of trolleys; though the connecting springs modify the analogy. *Pupils' Text* continues the thinking about molecules and sound.

Speed of sound Pupils should meet a demonstration of the speed of sound in air as a check on their calculation for air molecules. It is only an indirect check, setting a lower limit but it gives useful testimony.

And when it is measured at different pressures and found to remain the same we have valuable testimony: a suggestion that the speed of air molecules is itself independent of pressure. Then we have the missing link in the argument from our kinetic-theory result to Boyle's Law. (If v stays the same when P changes, v^2 stays the same and therefore we predict PV will stay the same, unless we change the temperature—and measurements with sound can even test the temperature effect too.)

Echoes take too short a time unless a large wall is available very far away; but teachers can use Year 4 apparatus for a fine demonstration: arrange the ticker-timer to make sharp electrical pulses and let a small microphone listen to them and show them on an oscilloscope.

(*Note:* The traditional scheme of holding a tuning fork over a glass tube partly filled with water and listening for resonance should be avoided. That hangs on a discussion of standing waves which is seldom well understood and would be quite out of place at this point when we are busy thinking about molecules handing on a compression through air.)

Demonstration 82 Speed of sound

This is a direct method, which avoids the mysteries of standing waves.

Apparatus

1 oscilloscope	item 64
1 microphone	167
1 timer	108/1
1 L.T. supply for timer	59
1 rheostat for timer	541/1
1 $1\frac{1}{2}$-volt cell	52B
1 small loudspeaker (e.g. earphone)	242
1 resistor (about 2 ohms)	
kitchen foil	571
1 drawing pin	

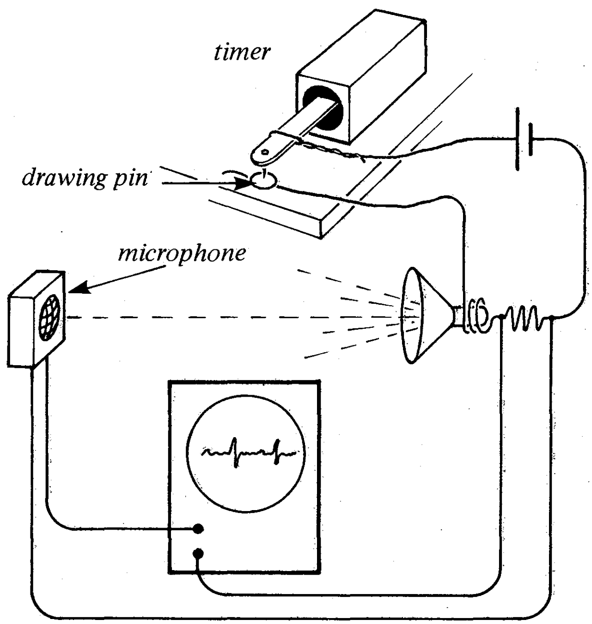
Arrangement

The ticker-timer acts as a pulse generator—making 50 pulses per second if the timer is polarised. The spike on its blade hits a drawing pin with a scrap of kitchen foil underneath, making brief contact which completes a d.c. circuit to give a pulse through the loudspeaker.

The microphone receives pulses of sound from the loudspeaker and shows them on the oscilloscope trace.

A very small sample p.d. taken from the loudspeaker circuit is inserted in series in the connection from microphone to oscilloscope. Then the very large pulse for that triggers the trace at the instant of each original pulse of sound at the loudspeaker. If that pulse is invisible, reduce the sampling resistance.

The position of the microphone's pulse on the calibrated oscilloscope trace indicates the time the sound takes to travel from loudspeaker to microphone.



Procedure

For most pupils, just point to the two pulses and say that their separation shows the time taken by sound to travel. If a measurement is required, proceed as follows.

Set the gain of the Y amplifier in the oscilloscope at the maximum value (0.1 volt/cm).

To obtain a known speed for the time-base, set the fine control knob in the CAL (calibrated) position, fully clockwise, and the X-gain at its minimum position, fully counter-clockwise.

Start with the microphone about $\frac{1}{4}$ metre from the loudspeaker and move it steadily away. Pupils will see the microphone's pulse moving along (and growing smaller).

Measure the distance that the pulse moves when the microphone is moved, say, $\frac{1}{2}$ metre. Find the time corresponding to that from the time base calibration. Thence calculate the speed of sound.

Note: The accuracy of the result depends on the accuracy of calibration of the oscilloscope. If the calibration is doubted, check by connecting the output of the 1000Hz oscillator of a scaler (item 130/1) to the Y-input. The frequency of the scaler's oscillator can be checked by letting it run for some time and checking with a watch.

Sound waves and atmospheric pressure Ask able pupils an interesting question, 'Would the speed be bigger or less if you could send a sound through a much thinner atmosphere, say at half the pressure and density but at the same temperature?' Some will enjoy reasoning that *if* molecules travel at the same speed, the sound would probably travel at the same speed. To many a pupil, thinking about this picture of air molecules handing on the clumping of molecules in a sound wave—as they move and make collisions—is an interesting business of putting theory to work. What seems obvious to us is new thinking for them.

The speed does *not* change. Mountain climbers who try echoes at 1500 metres will find the same speed though the pressure will be 25% smaller—the change of temperature makes only a small difference. If they carried a flute and a tuning fork on their climb, the agreement of their tuning when sounding the same note would not change much.

Demonstration 83 Critical test: Speed of sound in air at different pressures
(OPTIONAL)

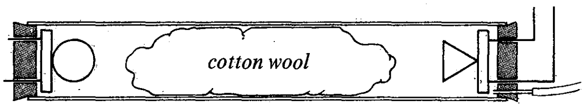
Apparatus

As for the previous experiment with the following additions:‡

1 pipe (glass or perspex or plastic pipe used by plumbers) 1 metre long, 5–10 cm diam.	
2 bungs to fit pipe‡‡	
1 Bourdon pressure gauge	67
1 vacuum pump	item 19/1
pressure tubing (2 pieces)	563
T-piece to connect gauge	
cotton wool	

‡ The loudspeaker must be small enough to fit inside the pipe. An earphone will serve. The microphone must be small enough too.

‡‡ One bung must have a glass or metal tube to take pressure tubing for the vacuum pump.



microphone *loudspeaker*

Procedure

The general arrangement is the same as for the previous experiment.

Place the microphone and the small loudspeaker near opposite ends of the tube. Run the leads through the bungs which then close the tube.

Some cotton wool placed in the middle region of the tube seems to make the record clearer—probably by discouraging standing waves.

Show the oscilloscope trace. Pump out the air to about $\frac{3}{4}$ atmosphere, then $\frac{1}{2}$ atmosphere, while pupils watch the trace, which will show that the speed of sound does *not* change.

Actually the pulse from the microphone *does* move momentarily if the pumping is rapid, because the air left in the tube cools momentarily. And by watching carefully pupils see the reverse effect, heating when air is readmitted quickly.

Explain how this suggests we can honestly predict Boyle's Law from $PV = \frac{1}{3} Nmv^2$.

Relative speeds Return to the general prediction, $PV = \frac{1}{3}\ Nmv^2$, and ask about molecular speeds for other gases. Suppose we have samples of several gases each of them of the same volume, each at atmospheric pressure and room temperature. Then P and V are the same for our different samples and the only things that can differ are v^2 and Nm ($= M$ the total mass). So to keep our equation true, v^2 will have to be smaller for a gas which has bigger M, greater density.

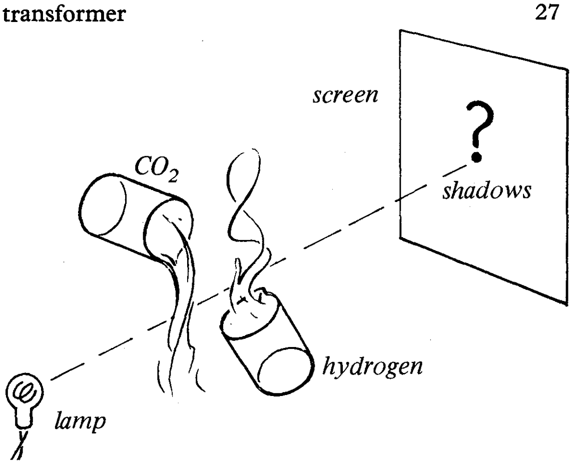
So we expect CO_2 (which is much denser) to have slower molecules; and hydrogen (which is much less dense) to have faster molecules—nearly 2 kilometres a second.

Pupils should see qualitative comparisons of densities, but only with a very fast group should we give values of gas densities or molecular weights and ask for estimates of molecular speed, using our result of the air calculation as a starting point.

Demonstration 84 Floating and sinking gases: different densities, hydrogen and carbon dioxide in air

Apparatus

carbon dioxide	
hydrogen	
compact light source	item 21
crude balance	10C
balloons	
transformer	27



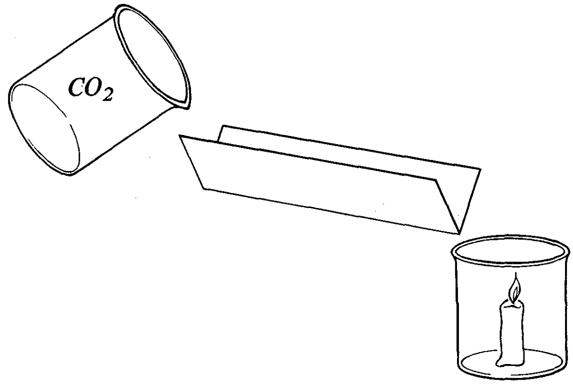
Procedure

Use the compact light source as a 'point' source to cast a shadow of the gas on the screen or wall. The shadow appears because there is unequal refraction by the gas and the surrounding air. For clear shadows the stream of gas should be at least $\frac{1}{2}$ metre from the lamp and the screen at least 2 metres further.

a. Pour carbon dioxide *downwards* from one beaker to another. Then pour hydrogen *upwards* from one inverted beaker to another.

b. Let gas emerge horizontally from a rubber tube connected to the cylinder or other supply.

c. Pour CO_2 into a beaker containing a small lighted candle.



d. Instead of pouring CO_2 directly on the candle, let it run down a sloping 'gutter' of stiff paper or card folded to make a long vee channel. The lower end of the channel should rest on the edge of the beaker with the candle.

e. *(Optional)* Fill balloons with air, CO_2 and hydrogen. Hold them, then release them.

Teachers may like to hang balloons of air, carbon dioxide and hydrogen on a simple metre-rule balance to show qualitative differences. (Measurements would take a long time and interrupt the present interest. Also, pupils might get entangled with Galileo's amusing paradox that if we weigh a bladder full of air and then let the air out and weigh the bladder again there is no change in the weighing—because of buoyancy. With a rubber balloon, there *is* a small change, on account of the extra pressure needed to inflate the balloon).

DIFFUSION

Diffusion fits in with our picture of gas molecules in constant motion in a vast open space and the slowness of diffusion is witness to their finite size (see discussion in *Pupils' Text* Chapter 8). Pupils should see at least one diffusion experiment now.

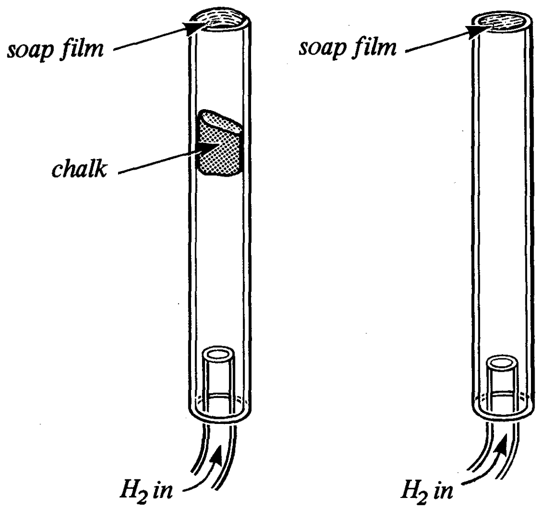
There are good traditional demonstrations that use an unglazed porcelain jar; but, for speed and clarity, we suggest two others: diffusion of bromine in air; and an ingenious demonstration that uses soft blackboard chalk.

Demonstration 85a Diffusion of gases

Apparatus

polythene tubing (2 15-cm lengths	item 228
blackboard chalk (soft)	
soap solution‡	569
hydrogen supply	
carbon dioxide supply	
retort stand, boss and clamp	503–506

‡ from toy shop, or soapy water and glycerine.



Procedure

Take a 15-cm length of polythene tubing which is slightly too small in diameter to take a 1 cm length of *soft* blackboard chalk. Warm the tube so that it can be stretched, and push the chalk a little way in. Hold this tube in a vertical position.

Make a flat soap film at the top end of the tube by smearing soap solution across it.

Feed hydrogen in through a fine tube inserted in the lower end of the polythene tubing. Hydrogen molecules pass more rapidly upwards through the chalk than air molecules pass *downwards*.

Soon there is a greater concentration of molecules above the chalk than below, where the pressure is atmospheric. The pressure above the chalk rises above atmospheric and blows a soap bubble.

Pupils will show a good feeling for scientific care if they raise the objection that simple buoyancy of hydrogen may well be the essential agent in bubble-blowing. If they do not raise that objection suggest it to them. Then show a control experiment: the same arrangement without any chalk. The buoyancy effect is barely noticeable.

Notes

1. The hydrogen is best obtained from a cylinder—small cylinders are often available from Chemistry departments. Failing this, obtain hydrogen from a chemical generator; but in that case pass it through a filter of loose glass-wool to remove small drops of acid which would spoil the soap film.

2. When the chalk has become wet with soap solution in repeated trials, its efficacy can be renewed by scraping it with a screwdriver, while it is still in the tube.

Demonstration 85b Diffusion of gases
(OPTIONAL ALTERNATIVE)

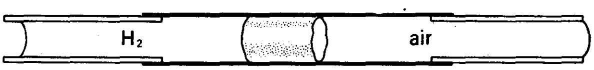
Apparatus

retort stand, boss and clamp	item 503–506
soap solution‡	569
hydrogen	
carbon dioxide	
polythene tubing, 15 cm	228
2 glass tubes, 7 to 10 cm	
blackboard chalk (soft)	

‡from toy shop, or soapy water and glycerine.

Procedure

This is a more elaborate version of the previous experiment. Use a piece of *soft* chalk as a diffusion barrier inside a *horizontal* piece of polythene tubing. Warm the polythene; push 1 cm of chalk in, and attach a glass tube at each end.



Fill the glass tubes with samples of two different gases such as hydrogen and carbon dioxide. Seal the outer end of each glass tube with a soap film. Then there are two samples of gas, each enclosed by a soap film at one end and a chalk barrier at the other.

Pupils watch the progress of the soap-bubble pistons to see the effect of diffusion.

Uranium separation by diffusion Perhaps mention the separation of uranium isotopes by a diffusion method. Uranium extracted from ore is converted into uranium hexafluoride, which when heated by steam becomes a dense vapour. That vapour contains molecules of two slightly different masses, because uranium has two kinds of atom, one slightly lighter than the other, and only the lighter, rarer kind is fissionable in ordinary circumstances.

To obtain fissionable material it is necessary to separate that lighter uranium from the rest; and that is done by diffusion of hot dense uranium hexafluoride vapour through a very thin porous barrier. As the molecules stagger through the barrier, the slightly lighter ones, which have a higher average speed, succeed in getting through slightly faster than the others. Then the mixture seeping through is a little richer in the lighter component than before. To effect any separation, the pores of the barrier must be smaller than the mean path of the vapour molecules or the mixed vapour will gush through unchanged.

This slight partial separation by diffusion has to be repeated in thousands of stages before a full enough separation is obtained. That process is presumably still in action as a major way of separating uranium, which is useful for making small power reactors as well as for warlike purposes.

A PRIVATE NOTE ON THE ADVANCE INTO QUANTUM PHYSICS

{**'Equipartition of energy'** In some of our later discussions we have to neglect one very important part of a professional physicist's kinetic theory of gases: equipartition of energy. Statistical studies, combined with the assumption that every molecular collision conserves momentum and conserves kinetic energy—that is, that the collisions are perfectly elastic—lead to the conclusion that all gases at the same temperature have the same *average* kinetic energy of molecular motion.}

{The full form of this theorem states that each 'degree of freedom' will have the same energy on the average. For the linear motion of molecules as they fly through the space of the container, there are three degrees of freedom, x, y, z. For a gas whose molecules are single atoms, (such as helium or neon) those three degrees of freedom, each with an equal share of kinetic energy on the average, are the only ones concerned.

Predicting the specific heat capacity of such a gas is easy and successful. For a molecule of more than one atom, (e.g. oxygen or carbon dioxide) there are other possibilities too: the molecule can rotate in various ways, and the atoms of the molecule may oscillate.}

{**The Quantum Restriction** At the beginning of this century, it seemed clear that equipartition should apply to the energy of rotational motions and vibrations. However, certain experiments—such as those measuring the specific heat capacities of gases over a wide range of temperatures—threw increasing doubt upon this. That doubt reflected doubt in turn upon the laws of motion and simple statistics which had made equipartition seem inescapable. Finally, it was realised that these doubts, combined with inconsistencies in other parts of physics, all pointed towards packaging of some forms of energy in quanta. We were forced to modify our view of nature and develop a quantum theory, forced by the failure of equipartition among other things.}

{**Equipartition holds for Linear K.E.** However, that failure in no way affects the kinetic energy of *linear* motion of molecules. We are as sure as ever that all gas molecules, at a given temperature, have the same *average* kinetic energy of linear motion. Since we still trust equipartition for that, we can write,

for any two gases at the same temperature:
average $\frac{1}{2}mv^2$ for molecules of one gas
$=$ average $\frac{1}{2}mv^2$ for molecules of any other gas.

This at once tells us we can compare molecular speeds if we know relative molecular masses. Chemistry could provide us with ratios of molecular masses; but those are often derived from gas densities; so we can use gas densities directly in our kinetic-theory comparison of speeds.}

{Also, as we shall see, $\frac{3}{2}PV$ tells us the *total* of all the $\frac{1}{2}mv^2$ values for all the molecules of a sample (that is, the number of molecules times average $\frac{1}{2}mv^2$); thus equipartition tells us that in equal volumes of two different gases at the same pressure and temperature, *the numbers of molecules must be equal*. Thus, *if* we trust equipartition, we can deduce Avogadro's rule and then we see why the ratio of gas densities gives us the ratio of molecule masses. Otherwise, if we do not have that assurance about the rule we must look very carefully at the chemical evidence, which Avogadro felt practically forced him to adopt his rule.}

{Unfortunately, equipartition would seem to pupils at this stage an outrageous statement about some unseen mathematics imposed mysteriously, so we cannot profitably use it, and that limits the uses we can make of our simple kinetic theory.}

{This discussion is nothing that we should give to our pupils but is inserted here as a reminder of something to keep in the back of our minds in teaching.}

CHAPTER 8

GASES III A GREATER PREDICTION—AFTER A HARD CLIMB

Measuring mean free path and estimating size of molecules and Avogadro number

ESTIMATE OF THE SIZE OF AN AIR MOLECULE

Offer to measure the size of a molecule and find out how many air molecules there are in the room. That is difficult, but with pupils who have the ability and interest it is well worth while—they are at last finding their bearings in the atomic world.

Again show bromine diffusing in air as the essential experiment, and let pupils estimate the progress of diffusion in a measured time.

From that, calculate the mean free path of one molecule wandering among others—the distance from collision to collision.

Also remind pupils of the volume-change from liquid to gas. That links our estimate of mean free path in open air with the size of an air molecule crowded into liquid.

A rough estimate of molecule diameter emerges, which we can use to estimate the number of molecules in a known volume (or the Avogadro number of molecules in a 'mole'); and thence the mass of a single molecule.

This offers a great extension of our kinetic theory discussion: we obtain a microscopic estimate of molecule size from macroscopic measurements. Although we shall now describe the argument in detail, we trust that teachers will not infer that this is an unavoidable part of our scheme, without which our suggested programme would somehow fall to pieces. It would be a great pity to give this discussion such extreme importance for all pupils because many who can follow most of our programme successfully would find it discouragingly hard.

On the other hand, we hope that every teacher will try out this discussion at least once. At a first glance, it looks unfamiliar and its arguments seem risky; so teachers may well doubt the feasibility of the suggested treatment when they read the account of it here. Tried out with a class, it has a much better chance of proving feasible, because it offers pupils an exciting chance to join in an atomic measurement. What seems difficult to us on account of our background of knowledge may seem much easier to pupils. We offer them 'a guided trip up Mount Everest'.

{**Difficulties and doubts** The success of this part of our course depends very strongly on the attitude and feeling of each of us teaching it. We have a chance here to delve into the atomic world with our young pupils, and let them feel that they themselves have measured molecules and counted their number. Pride in that achievement will not be spoiled by the honest knowledge that the results are very rough estimates. But that sense of living in the atomic world is delicate: it can easily be killed by doubt, by worry, even by well-meaning care in precise teaching. The teacher needs to be a guardian against worries as well as a skilful guide.}

{The essence of a good scientific method is here—this is one of the early classical estimates of molecules in the last century—but in dealing with the geometry of collisions and the statistics of a chaos of a myriad molecules, we must take many short cuts, round off some numbers, settle for a simpler average than the 'proper' one, and forget a dozen refinements of professional treatment. Yet if we can turn a blind eye to those shortcomings of the simple treatment, we shall find the essence of the estimate is there, and our pupils will understand it.}

{This is a rare case in our teaching where doubts about short cuts will not so often come from pupils as from our own pride in careful teaching. Yet this is a case where we could afford to be lighthearted, so that we carry our pupils with us. We should perhaps feel the warning in Browning's 'A Grammarian's Funeral':

'This man decided not to Live but Know.'

Can we leave our own doubts in the background for once? If so, we, or rather our pupils, can make rough guesses and leave out correcting factors, yet emerge with knowledge to be proud of.}

{Of course if pupils do raise doubts, we must reassure them with honest answers.}

{In making our estimate, we shall leave out factors like $\frac{1}{2}$ or $\sqrt{\pi}$. We shall be careless in some of our steps. We need to take those short cuts in a holiday spirit.}

{All through this experiment, and the reasoning that goes with it, the overall assurance to teachers and to pupils is this:

> 'This *is* a rough estimate, but it is worth while because it gives us an actual measurement of the size of a molecule. We do have to make rough guesses and to leave some details out; so it is not accurate. But it follows a real method of measuring molecules and will show you how that is done. And its result will not be a wild guess but a rough estimate, well worth having. This is desperate physics'.}

Programme The work leading to knowledge of molecule sizes goes through several stages.

Start by reminding pupils of an earlier comment: that the slow diffusion of bromine in air tells us that gas molecules are not infinitely small. Instead of flying up the tube, the bromine molecules are stopped by collision after collision with air molecules. If both bromine and air molecules had no size at all ('pinheads'), the bromine molecules would see no targets to hit: they would travel straight on. The bigger the air molecules (and the bromine molecules), the bigger the targets to hit, the shorter the path between collisions, and the slower the net progress of diffusion. Arguing backwards from that, we can extract an estimate of molecule size from the slowness of diffusion. Teachers may like to show the diffusion of bromine (Demonstration 86) at this point—as a preview.

Stage 1 Mean free path Pupils watch bromine diffusing in air, and time its progress. From that we shall estimate the length of a bromine molecule's path from one collision to the next, or rather the *average* length for a great many bromine molecules; we call that the *mean free path*.

We can see how fast the brown bromine seems to travel as a crowd: we can time its advance. But that advance is really the result of an enormous number of short staggers from collision to collision, in all kinds of directions—a multitude of Brownian motions.

Stage 2 Random walk In mathematical texts the problem of the 'random walk' is posed and discussed with many special conditions; and both the result and the calculation that lead to it look very complicated. Fortunately, the result we need here is simple. We can offer crude algebra to some pupils and all can make a rough experimental test of the result. The test is equivalent to throwing dice and making a survey of the results. We describe a random walk and tell pupils the result:

> Suppose someone takes a walk of 25 equal strides, starting afresh, in a new direction at random, after each stride. (Gamow* calls this *the drunkard's walk.* He describes a reveller starting for home in a thick fog.) How far will that person progress, from start to finish as the crow flies? OFTEN very little—the tourist on a clouded mountain top often returns to his starting point. VERY SELDOM, 25 strides. If he tried that walk of 25 strides an enormous number of times, what would his AVERAGE progress be? Statistical enquiry says 5 strides.

Pupils test that by imaginary walks plotted on graph paper.

In general, for a walk of N strides the *average* progress in a huge number of trials is $\sqrt{N}$ strides.

We tell pupils that and ask them to test the rule with $N = 25$. First they watch a random walk.

Popularity This kind of experimental support for the random walk expression goes well with pupils. However, some difficulties may appear in the discussion of this test; then misunderstandings cloud the issue. So we offer teachers an algebraic discussion at the end of this chapter.

Bromine's random walk Then we apply that rule to the diffusion of bromine. That enables us to estimate the mean free path of a bromine molecule in air—and, what is much the same, of an air molecule in air. Then we use some 'target geometry' to estimate the diameter of an air molecule.

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* *One, Two, Three, ... Infinity* by G. Gamow (Macmillan 1956; paperback edition, Muller).

Class Expt 87 Watching a random walk: mean free path

Apparatus

1 two-dimensional kinetic model kit — item 12
Pupils work in pairs

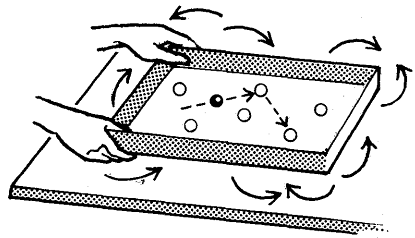
Procedure

Pupils follow these instructions.

* * * * *

Put several dozen marbles in your tray, with one distinctly coloured marble which is different from all the others. Agitate the tray and watch the path of the marked marble among the others. Watch its random walk from collision to collision.

Then if you like make a rough estimate of the marble's *mean free path*—more for the sake of understanding the idea than for a measurement. The mean free path is the average distance of travel from one collision to the next.



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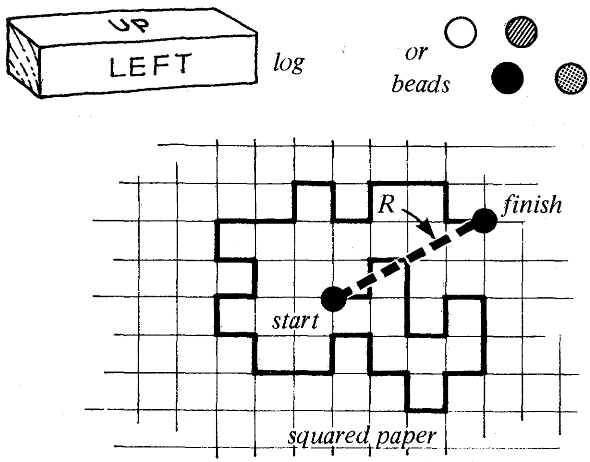
Class Expt 88 Test of a random walk

Apparatus

100 sheets of paper ruled in squares — item 235
32 'random indicators': *either* 1 'log'‡ per pupil
or 1 bag of balls‡‡ per pupil

‡ The 'logs' are small rectangular blocks of wood. Buy cheap wood strip of square section, say 1 cm × 1 cm, and cut it into 5-cm lengths. Before chopping up the strip paint the long faces four different colours to signal a move UP, DOWN, LEFT or RIGHT (or mark the faces of each log U, D, L, R).

‡‡A bag of balls or beads is more expensive but it gives a stronger feeling of chances in a concealed lottery. Balls of plastic or wood in four colours can be bought from suppliers of primary school equipment. At least one dozen balls (3 of each colour) should be in an opaque bag and each pupil should have a bag. The bag must conceal the balls fully. Bags made of denim are best, and last well. Small bags of dark plastic (e.g. for wine bottles) are not opaque enough. For a cheap opaque design we suggest an ordinary brown paper bag *inside* a polythene lunch bag for protection.



Method

Each pupil plots his own random walk, taking his cues by throwing a 'log' like a die, or by picking a ball from a bag. In the latter case he must return the ball to the bag after each move and shake the bag to ensure a fair choice next time.

The log (or the ball) tells the pupil to take a stride of one unit, up, down, left or right according to its colour (or other marking). The unit may be the side of the squares ruled on the paper. (Paper ruled in centimetre squares has an obvious advantage. It is available from suppliers for primary schools and relatively cheap. We do *not* suggest buying expensive graph paper.*)

Procedure

The pupil marks a starting point on his paper and draws a pencil mark of 25 strides. He measures the resultant 'crow flies' distance from start to

* In the first edition we suggested isometric grid paper with three rulings at 60°. Pupils threw dice to find the direction of each stride along the six directions. That is no better in statistics; it is more artificial and expensive.

finish, using a strip of the same squared paper. He brings his result to a central record on the blackboard.

One such walk will take 5 to 8 minutes. Each pupil should make at least three such trials.

Averaging the record. On the blackboard add all the resultant trips (each of 25 strides at random) and find the plain arithmetical average.

If pupils complain that this statistical averaging seems inaccurate, point out that the real game is being played not by a few dozen pupils plotting a wandering path but by millions of millions of millions of brown bromine molecules carrying out random walks on a vast scale.

Tell pupils that the $\sqrt{N}$ rule is the prediction for a special kind of average. For the ordinary average the prediction is 20% smaller, $0.8\sqrt{N}$. We ask the class to see whether our average of all their walks (each 25 steps) comes out anywhere near to $0.8\sqrt{25}$, or 4. If the result is far from 4, we shall have to say regretfully that we are playing our test game with far too few trials. That may encourage some pupils to continue the trials on their own—if so, we should welcome any results they bring in, and include them in a new average. Interest in this may even lead to a feverish business of running more trials—and, since statistical ideas are important in science and other studies, that particular feverish interest is probably one to be encouraged.

In our bromine estimate we shall forget the factor 0.8—this is 'desperate physics'* involving several other short cuts as well.

The 'proper' average To get even close to the ideal $\sqrt{N}$ value, we should have to take the *root-mean-square average*—as the algebra will show. That is: take each pupil's measured distance and square it; add the squares of all 100 measurements; divide by 100 to find the mean square; and take the square root of that.

Not only would that r.m.s. averaging involve considerable extra work for the teacher but it would make the test itself seem confusing to pupils.

The only exception, on both scores, would be with a fast group to use a pocket calculator that has keys for squares and square roots.

The simple average If, instead, we take the *simple arithmetical average* of the 100 distances, the ideal result is about 0.8 of the previous one. (Instead of $\sqrt{N}$ we expect $\sqrt{N} \times \sqrt{2/\pi}$ or about $\sqrt{N} \times 0.8$.)

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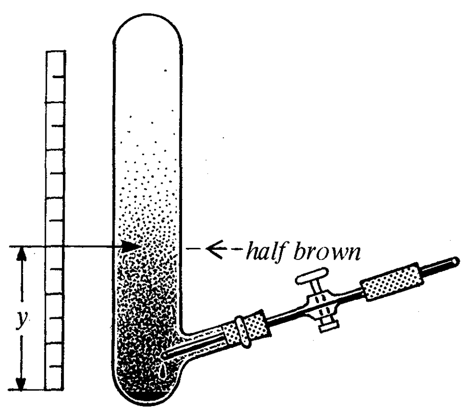
* As one might say to pupils, 'In the world of atoms, we are glad to make a rough estimate *at any cost*.'

Demonstration 86 Measuring the diffusion of bromine in air

Apparatus

As Demonstration 76, with:

centimetre rule	item 502
pencil	
clock	



Procedure

Release bromine in the tube of air as before. Start the clock.

Explain to pupils that they will be asked to estimate the progress of the brown bromine after 500 seconds from start.

At the end of, say, 8 minutes, point to the thick bromine vapour at the bottom of the tube: 'full brown'; and to the clear air near the top: 'clear'.

Then at the end of the 500-second period ask pupils to vote for the height at which they see 'half brown'. Hold a ruler beside the tube, and run a horizontal pencil up the tube, calling the height every centimetre: 1, 2, 3 . . . 8, 9, 10 . . . 15, then back down again.

Collect the votes. Average them or arrive at an agreed sample value.

If, as is likely, the votes cluster near 10 cm, it may save time and trouble to take 10 cm as the 'half brown' distance, telling pupils who voted differently they can always carry out the next stages of the calculation with their own vote.

A simple timing of the bromine crowd's advance will not tell us the mean free path, unless we know the connection between a random stagger of many free paths and the overall advance. And that calls for help from statistics.

Calculation: the bromine estimate leads to mean free path

Pupils have watched the diffusion of brown bromine vapour in air and have estimated its average progress in 500 seconds. Here are suggestions for discussion:

Apply the $\sqrt{N}$ rule to the estimate. As an example here suppose their estimate is 10 cm to 'half brown'.

Suppose a bromine molecule makes N collisions in 500 seconds (usually with air molecules) with one stride from collision to collision.

Bromine molecules, being more massive than air molecules, have an average speed of only 200 metres/second.* Then how far will one of them travel in the clocked time of 500 seconds? What is its total, straightened-out distance (not its random-walk progress)? (Some pupils prefer to call this the 'unravelled length of its path'.)
(200 metres/sec) × (500 sec) = 100000 metres

Isn't that amazing, a hundred thousand metres, 100 kilometres, in 500 seconds?

But then they don't get very far—you can see they don't—only 10 centimetres on the average, because they make so many collisions. Each molecule must make an enormous number of collisions if its *net* progress is so small in that time.

If, on the average, a molecule only progresses 10 cm, (0.1 metre), it must make an enormous number of short strides between collisions, on the way. How many strides in those 500 seconds? Use the random walk rule to find out. Suppose the answer is N strides.

Then straightened-out path = N strides

$$N \text{ strides} = 500 \times 200 \text{ metres} \quad \ldots[\text{A}]$$

$$\text{Random walk progress} = \sqrt{N} \text{ strides}$$

$$\sqrt{N} \text{ strides} = 0.1 \text{ metre (in this example)} \ldots [\text{B}]$$

$$\text{Divide [A] by [B]}, \quad \frac{N}{\sqrt{N}} = \frac{500 \times 200}{0.1}$$

$$\sqrt{N} = 1\,000\,000$$

$$\therefore N = 10^{12}$$

Number of collisions: a bromine molecule makes 1 000 000 000 000 collisions in its random walk of 500 seconds.

Mean free path One stride is $\frac{500 \times 200}{10^{12}}$ or 10^{-7} metre, or 100×10^{-9} metre.

* From the vapour-density measurements, we know the molecular weight of Br_2 is 160 compared with about 29 for air. Kinetic theory suggests [500 metres/second] × $[29/160]^{\frac{1}{2}}$ for Br_2.

Value of mean free path The method we have used is one of the great classical approaches of the last century. There are other methods, depending on measurements of viscosity, estimates of Van der Waals' constants, etc. The results differ somewhat according to the method chosen. For air at room temperature, older estimates gave 80 to 100 $\times 10^{-9}$ m, but the modern value (from modified statistics) lies between 60 and 70×10^{-9} m. In the following discussion we shall take the round number 100×10^{-9} m.

Collisions Return to the number of collisions that an air molecule makes each second. That will be different from our experimental estimate for bromine molecules because O_2 and N_2 molecules move faster. We combine our estimate of molecular speed with our estimate of mean free path. In one second a molecule of air travels 500 metres of *straightened-out* path, and that distance contains $500/10^{-7}$ mean free paths. So the molecule makes 500×10^7 or 5 thousand million collisions in one second.

We still do not know the size of a molecule, or how many molecules there are in any sample of air, such as the air in a room. But we already know that a room full of air is also, so to speak, a room full of collisions. There is no question of these collisions being anything but elastic, because if any energy disappeared in a collision, say by some mysterious radiation, the air in the room would be down on the floor in a fraction of a second.

Time for a long journey Pupils can also calculate how long, on the average, the molecules on one side of the room would take to wander across to the other side of the room *if there were no convection currents to sweep them across as a crowd.* Diffusion, as we now see it, is not a motion of the whole crowd.

(Even with the strong driving field provided by hunger, a passenger in a train 'diffuses' slowly down a crowded corridor to the dining car. But the train carries the whole crowd in a very rapid 'convection current'.)

Specimen calculation In time T (measured in seconds), the total straightened-out path of a molecule is 500 T metres. The number of collisions it makes in that time is:

500 T metres/(mean free path),

or 500 $T/10^{-7}$, or 5×10^9 T.

The average progress from start to finish will be $\sqrt{N} \times$ (mean free path),

or $\sqrt{5 \times 10^9 \times T} \times (10^{-7})$ metres.

Suppose the room is 6 metres wide (a large room). Then, for molecules to get across the room, average net travel,

6 metres $= \sqrt{5 \times 10^9 \times T} \times 10^{-7}$

$\therefore$ $T = 720\,000$ seconds, more than one week for a molecule to get across a room of completely still air.

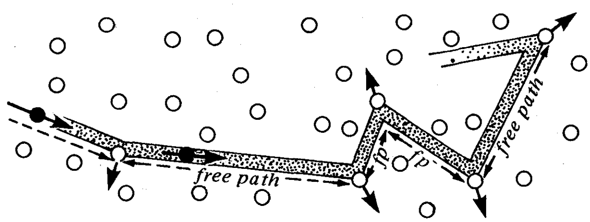
ESTIMATE OF MOLECULE SIZE

This is the method given in standard text books of properties of matter.

We have estimated the mean free path for bromine molecules diffusing through air. We guess that the mean free path of an air molecule is much the same—within our rough estimating. That mean free path leads us to the size of an air molecule.

Collisions and free path Sketch a snapshot of air molecules in random disorder, all the same size (e.g., the size of a 2p coin) spaced 9 or 10 diameters apart.

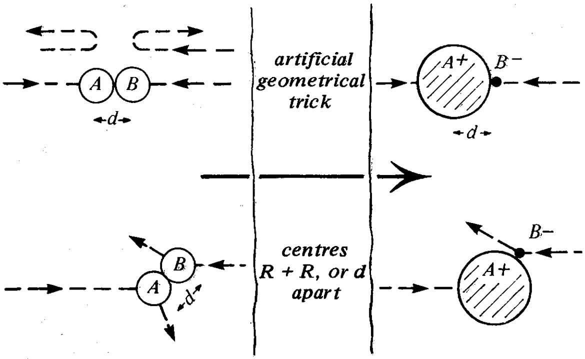
Point out that to find how one molecule would move through this vast array of moving neighbours is too difficult a business. Instead, we pretend that all the molecules are at rest except one and watch that one molecule go hurtling through the crowd.



Take a piece of chalk of *length equal to the sketch of a molecular diameter* and draw the path of our chosen molecule, holding the chalk sideways so that it makes a white strip one molecular diameter wide. When this path finally meets one of the other molecules, there is a collision. Bend the path and proceed in a new direction until there is another collision. (As we shall find, the mean free path is many times the average spacing between molecules; so we should draw our missile molecule passing by many target molecules before it makes a hit.)

Now move to a separate preparatory discussion of a collision in detail. Draw a large round molecule bouncing against another large round molecule and ask how far apart they are, *centre to centre,* at the collision. The answer is (radius + radius), or one diameter apart. Then the discussion might run like this:

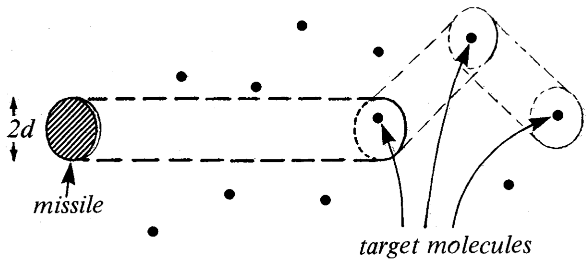
I am going to show you a trick for finding out how far a molecule goes before it hits another. This is a trick which has been invented by scientists, and



it is not what really happens; but if you watch carefully you will see it will give good results and you will be glad to be able to use it.

When molecules collide their centres are always (1 radius + 1 radius) apart—that is, 1 diameter apart. Instead of sketching two equal molecules colliding like that, we could pretend that the molecule flying along to make this collision is much bigger, and the other molecule that it hits is much smaller—we shall see the same event, a collision with the molecules' centres one diameter apart.

We push this imaginary trick to the limit and give the travelling molecule double size, so that its *radius* is just one molecule *diameter*. Then we must make the other molecule that is hit have no size at all: we draw it as a point.

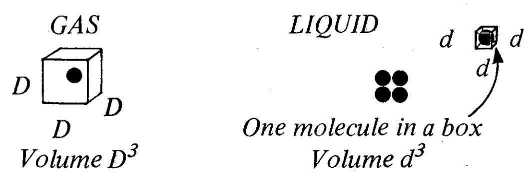


Now we can start the story all over again. The missile molecule flies along, an artificial molecule with radius one molecule diameter. It flies along marking out a broad strip two diameters wide. All the other molecules are shown just as points. Where must one of these be if it is to be hit by the flying molecule? That point must be anywhere on this wide chalk track. Then there will be a collision. So here is the story: the flying molecule travels along until here, where it hits a molecule that is on its path, so it bends its path, flies along like this; here it hits another molecule; and so on.

Now let us think about the path swept out by this flying molecule which is possessively patrolling its 'share' of the volume of the containing box. We are pretending that this extra big molecule is a round ball of *radius* d, the diameter of a real molecule. What shape in space does it sweep out, as it flies along? . . . Yes, it sweeps out a cylinder. What is the cross-sectional area of that cylinder . . . ? Yes, not πr^2 but in this case πd^2, where d is the diameter of a real molecule. How long is that cylinder between one collision and the next? You already know that. That is the distance from collision to collision which we call, in the average, the mean free path. We have measured that with our bromine experiment. In ordinary air it is 10^{-7} metres.

In describing this cylindrical path which makes a bend at every collision, we might say 'like a bent gutter pipe', or a 'bent sausage', to make the picture clearer.

We are nearly there; we have nearly arrived at the actual size of a molecule. But first we must bring in some more information. We need to know the *volume of space* that belongs to one molecule in the air in this room.



The volume change from liquid air to air is about 1 to 750. If we say, as a rough guess for liquid air, suppose that each air molecule of diameter d occupies a cubical box of side d and volume d^3; then in ordinary air the space for each molecule is $750\,d^3$, on the average. Then, $D^3 = 750\,d^3$.

Now look back at the place where we left our calculation from the mean free path. We have one doubly fat molecule tracing out a 'bent sausage' cylinder through the gas in which all the other molecules are just points. From one collision to the next, that missile molecule sweeps out a cylinder of area πd^2 and of length one mean free path, 10^{-7} metres. The volume of that sausage between one bend and the next contains just one target molecule for the missile to hit. So that volume is $750 d^3$.

Therefore $750\,d^3 = \pi d^2 \times 10^{-7}$.
Cancel d^2 and move 750.
$\therefore d = (\pi \times 10^{-7})/750 \approx 0.4 \times 10^{-9}$ metre

We have found the diameter of a single molecule of air. An atom is probably about half that size. This is certainly a rough estimate because our measurements were difficult and we have had to make all kinds of risky moves in carrying through our calculations. But yet this is a good estimate for many working purposes. It is in the right county, it is of the right 'order of magnitude'.

WHAT DOES MEASURING ATOMS MEAN?

When they have arrived at that rough estimate of an air molecule's diameter, teachers and pupils may ask how big an air molecule 'really is'. Precise measurements give 0.37×10^{-9} metre. But careful measurements lead to somewhat different diameters according to the experiment chosen and the method of interpretation used.

After all the diameter of a molecule is not as definite a thing as the diameter of a steel ball or even the diameter of a man's head. Not only is an air molecule 'oblong', but it behaves as something 'squashy', so that more violent collisions are likely to reveal a smaller effective diameter.

In commenting to pupils on the size of atoms we should keep in mind the close interaction between the measurements and Nature. The estimates we get from oil films are for molecules or atoms lying side by side or loosely attached to other atoms, and the estimate here is for air molecules making mild collisions.

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 demon 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 light-weight 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.

NUMBERS OF MOLECULES

After reaching an estimate of the diameter of an air molecule—a result somewhere between 0.1×10^{-9} and 0.9×10^{-9} metre—we can estimate the number of air molecules in, say, the classroom.

Now that we know the diameter of a molecule, we can go back to the space, d^3, 'occupied' by a molecule in a liquid, and thence the space in open air.

Suppose we arrived at 0.4×10^{-9} metre for d. Then $d^3 = (0.4 \times 10^{-9})^3$ and

$$D^3 = 750 \times (0.4 \times 10^{-9})^3$$

Divide the volume of a room by D^3 to find how many air molecules there are in it. In a room 8 metres $\times$ 5 m $\times$ 3 m there are about $25\,000 \times 10^{23}$ molecules.

A number for Avogadro A mole of any gas is M grams, where M is molecular weight of the gas. It occupies 22.4 litres at 0°C or about 24 litres at room temperature and atmospheric pressure.

Therefore 1 mole contains

$$\frac{(24/1000 \text{ metre}^3)}{750 \times (0.4 \times 10^{-9})^3} \text{ molecules}$$

So our estimate for the Avogadro number would be 5×10^{23}.

The standard number for a mole is 6×10^{23}.

Where does that number come from? From measurements and arguments just like those we have carried through, though in fuller and more careful form.

Some pupils will have that number given to them in Chemistry, and we owe it to them to show them that they now know how it was obtained.

Either in class, or in a problem for homework, pupils should repeat a calculation like that above, to find the number of molecules in 24 litres.

We should rejoice over good luck if their estimate of the Avogadro number comes as near as 4 or 9 to the expected 6 in 6×10^{23}.

The essential measurement, the pupils' judgment of the distance for 'half brown', comes into that final result to the sixth power; so a change of 10% in that measurement will make a change of a factor of 2 in our result! Teachers who try this experiment with pupils will find that the general voting does not range more than about 10% either side of the average vote.

Comparison of molecule size with oil film measurement Of course we should now compare our estimate of air-molecule size with the measurement made with an oil film spreading. In Year 1 the olive oil seemed to have a molecule about 1.6×10^{-9} metre long. If we make use of chemical knowledge about the oil molecule, and divide by a dozen atoms, we get about 0.13×10^{-9} metre for a carbon *atom's* diameter; so it is not surprising to find 0.3 or 0.4×10^{-9} metre for an air *molecule*.

Results *We* know the importance of molecule size, Avogadro number, etc; but to pupils who have been taken through this chapter of new measurements and new thinking the outcomes are likely to be fuzzy unless we give a summary. *Pupils Text* ends Chapter 8 with a table of data for air molecules. That was given in *Teachers' Guide* for Year 3 but now pupils can understand its source.

NOTES TO TEACHERS

{**Expectations** The rule we have given is correct for a random walk in two dimensions or in three dimensions. But, like any statistical rule, it only tells us the probable result of averaging a large number of trials. The result of a single walk may be far away from the value given by the rule; and the average of a few walks may be quite far away, or it may be close. The averages of several sets of walks may range either side of the rule's value.}

{Suppose each pupil plots a random walk of 25 steps and measures the distance from start to finish, in steps. Suppose 100 pupils do that (or 33 pupils carry out the walk three times each). When we average the 100 start-to-finish distances measured by the pupils, we hope to emerge with the square root of 25, or 5 steps. With only 100 trials there is a considerable chance of deviation from 5. As likely as not the final average will be 4 or 6. Even so, the result will be far away from the extreme 25 steps straight ahead, and perhaps near enough to 5 to lend some support.}

{Furthermore, we must *either* take an r.m.s. average *or* apply a factor 0.8.}

{Since pupils will take the plain average, we had better give them the rule in the less simple form, that we expect the average of the start-to-finish distances to be $0.8 \times \sqrt{N}$. In practice with only 100 trials, that 20% change in our formula competes with the kind of deviation, say also about 20%, that we may expect as a result of taking so few trials. We could reduce the latter trouble to 10%—by taking 400 trials—but that would certainly take too much time. Instead, we must secure the goodwill of our pupils in making a very rough test of the statistical rule.}

{**Three dimensions?** When we consider the diffusion of bromine molecules up the tube, the mean free path is so small that to most molecules the sides of the tube are infinitely far away; so we should think of each molecule making a random walk in three dimensions. And yet we measure progress in one dimension, the vertical. Perhaps we should not use the full mean path but only a component of it. However once we begin considering such modifying factors, we are worrying about refinements which we are not justified in pursuing here.}

{**Correcting for bromine molecule size?** Teachers will realise that in this very rough calculation any attempt to make a correction for bromine molecules being bigger would place unscientific emphasis on precision in one particular place where we know we are being imprecise overall. Judging from relative densities of liquids and relative molecular weights, bromine molecules have a diameter about 1.2 times that of air molecules. That makes the 'average diameter' for a bromine molecule hitting air molecules 1.1 times an air molecule diameter. Then a bromine molecule probably has a mean free path among air molecules about $(1.1)^2$ smaller or 1/1.2 times the mean free path of an air molecule in air.}

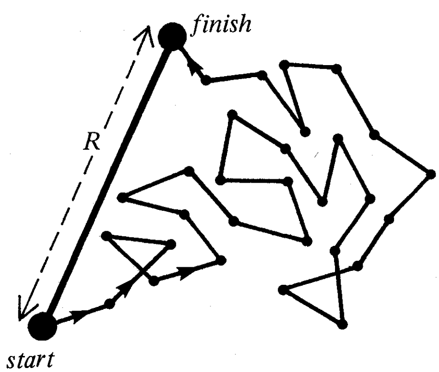
Other doubts And in this very rough calculation, we have made no attempt to decide what kind of average should be used for the resultant in a random walk treatment. Does the estimate of 'half brown' fit best with a root mean square average of the random walk of bromine molecules, or should we use the plain arithmetical average? Since we estimate progress in a vertical direction alone, should we take some component of velocity, or of mean free path? Unless we give up our simple experiment, in which pupils make a guess, and resort to colorimetry and density measurements, these questions must remain unanswered, as matters of choice and taste rather than definite knowledge. Nor would it be sensible to try to answer them here—that would miss the point of proceeding quickly in a simple story so that we do not lose our pupils on the way.

{**Private note to teachers: the random walk calculation with algebra** Here, just for interest, is a crude treatment of the 'drunkard's walk'. We do not suggest it for O-Level teaching.}

{If a man takes a large number (N) of strides each of the same length (L) in succession, but in random directions, what is his resultant distance (R) of travel?}

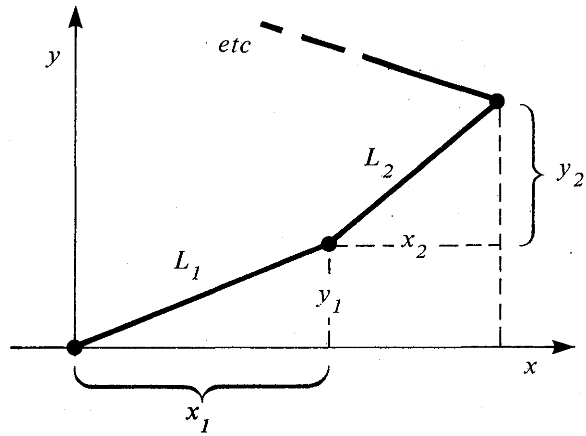
{Obviously this will vary from one batch of N strides to another: and may often be zero (in the cases when he comes back to the starting point) and may be as large as NL (in the very rare cases when he happens to take all strides in the same direction). We want the *average* distance from start to finish, *averaged over many batches* of N strides.}

{We observe a walk of N strides and find the resultant travel-distance R from start to finish. We observe a large number of such walks starting afresh each time and find the average value of R for



all those walks. Because it leads to the simple result, we find the average value of R^2 and take the square root, obtaining a root mean square (R.M.S.) average. We can show that this average should approach the value $\sqrt{N}L$. Here is a *two-dimensional* proof. The three-dimensional one is similar.

Sketch the first few strides of a random walk. Choose a set of perpendicular axes, x and y, arbitrarily. Using x- and y- coordinates, resolve



stride no. 1 into components x_1 and y_1, stride no. 2 into x_2 and y_2 and so on. Then the resultant of that walk, R, has

x-component $(x_1 + x_2 + \ldots + x_N)$

and y-component $(y_1 + y_2 + \ldots + y_N)$

and

$$\begin{aligned} R^2 &= (x_1 + x_2 + \ldots + x_N)^2 + (y_1 + y_2 + \ldots y_N)^2 \\ &= x_1{}^2 + x_2{}^2 + \text{etc.} \qquad + 2x_1x_2 + 2x_1x_3, \text{ etc.} \\ &\quad + y_1{}^2 + y_2{}^2 + \text{etc.} \qquad + 2y_1y_2 + 2y_1y_3, \text{ etc.} \\ &= L^2 + L^2 + \text{etc.} \qquad + ZERO \\ &= NL^2 \end{aligned}$$

The 'cross terms', such as $2x_1x_2$, add up to zero in averaging over many walks, because those terms are as often negative as positive, and they range similarly from 0 to $2L^2$. Similarly for the y- 'cross terms'.

Then average value of $R = \sqrt{N}L$

The proof is better if we use trigonometry and resolve each stride, L, into horizontal and vertical components $L \cos \theta$ and $L \sin \theta$. Then the cross terms in the expression for R^2 form $2L^2 \cos (\theta_1 - \theta_2)$, etc., and we argue that the cosines are as often positive as negative.

SECTION III

UNIVERSAL CONSERVATION POWER AND HUMAN ENERGY

Chapter 9 deals with the foundations of the Principle of Conservation of Energy—the experiments and arguments that established our belief.

The chapter begins with a brief word about heat and molecular motion before returning to simple measurements of heat with water—to make sure that any earlier treatment has left clear knowledge.

Then pupils are ready to read for themselves, in the corresponding chapter in *Pupils' Text 4*, the main discussion of Heat and Mechanical Energy. They read about the great series of experiments which convinced scientists that heat must be counted among the other forms of energy, and measured interchangeably with them. Then pupils themselves judge the results.

That is one of the best examples we can give of building up a tremendous body of evidence, and then feeling so confident that we generalise the conclusion.

Chapter 10 treats Power and its measurements in mechanical transfers.

Then there is a discussion of human energy-needs and supplies—placed here because data of our uses of food energy are really expressions of power, energy-transfer per day, etc.

Transfers of electrical power are discussed in Chapter 13.

CHAPTER 9

ENERGY AND ITS GRAND TOTAL: CONSERVATION

HEAT AND MOLECULAR MOTION

We have developed our idea of the kinetic theory of gases—a 'grand conceptual scheme'—and we have seen that it covers a good deal of experimental knowledge of gases and enables us to make predictions and to increase our understanding. Now it gives us a convenient link with ideas of mechanical energy.*

Looking back on the kinetic theory expression for PV, we see that it contains the kinetic energy of motion of all the gas molecules.

If $PV = \frac{1}{3}Nmv^2$, then $N(\frac{1}{2}mv_{av}{}^2) = \frac{3}{2}PV$. Now that we know the molecules' speed, we can in fact calculate the total kinetic energy for any given sample of gas. If we imagine the gas heated up, without change of volume, so that the pressure increases, we can calculate the new value of kinetic energy. We may well imagine that the heat which we have put in to warm up the gas has gone to increase molecular kinetic energy.

{**Note on changes of energy in a gas** When a confined gas is heated, it gains thermal energy in the form of increased molecular motion. Some of that is kinetic energy of random motion of molecules; but with many kinds of gas molecule there is also a gain of rotational energy and sometimes of energy of vibration as well. All that is what the heat energy of the gas consists of; there is no store of elastic potential energy, *except* the P.E. of the (P.E. + K.E.) of vibrational motion.}

{Pupils sometimes think of gas at high pressure as being like a compressed spring with 'strain energy'. If we compress a gas by pushing a piston quickly into a cylinder, the gas grows hotter, and all the energy transferred from us to the gas goes into thermal energy of molecular motion. If we let the compressed gas cool back to the original temperature, it loses all the thermal energy that it gained; then all the energy that we transferred to the gas has escaped to the outer world. The compressed gas, back at the room temperature, has no extra energy by virtue of being compressed—unless the molecules are so extremely close that the mutual potential energy of their force-fields is appreciable, as it is in a liquid.}

{Yet we can make a gas transfer energy to other things by letting it push a piston out with its high pressure. True, but the energy it then supplies will be provided by the gas cooling down below room temperature.}

Thermal energy given to a gas We can calculate, in joules, the increase of molecular kinetic energy when a gas is heated. We can also measure it experimentally—a measurement of specific heat capacity. It is difficult to demonstrate such a measurement for a gas; but we can tell pupils the result if we wish, and we can imagine an idealised way of obtaining it by heating a sample of gas electrically, measuring the energy input with voltmeter, ammeter and clock.

We might hope to find that the energy taken from an electric supply to heat a sample of gas agreed with our calculated increase of kinetic energy of motion of the gas molecules. We should

* In earlier stages, we should not say anything about heat and energy that would make the historical discussion look stupid or pedantic; yet we can profitably start pupils with a description of heat as associated with molecular motion, in the light of kinetic theory of gases, much as Tyndall, long ago, named his book *Heat, a mode of motion*.

find this true for a gas such as helium* or neon, in which the molecules are single atoms that do not indulge in rotation or vibration that can be increased by heating. However, for other gases, such as air or carbon dioxide, the electricity supply has to deliver more energy than goes simply into the kinetic energy of molecules flying about in the gas. The extra energy goes to provide for rotational motions and vibrations of molecules.

All this is private knowledge that a teacher keeps at the back of his mind in dealing with heat and mechanical energy.

† SIMPLE MEASUREMENTS OF HEAT

Pupils who missed Year 2's class experiments in simple calorimetry should try them quickly now.

† Demonstration 89a Exchanging heat between hot and cold water

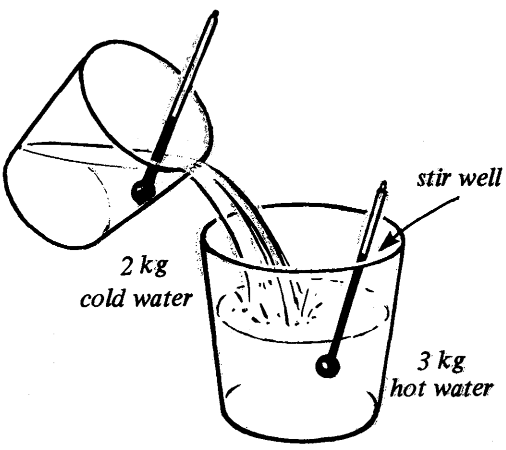
Apparatus

2 plastic buckets	item 533
1 demonstration thermometer‡	145
1 balance	20
kettle of hot water	

‡A good, visible, demonstration thermometer is now available. This simple demonstration is important enough to warrant buying the instrument. Otherwise, use an ordinary mercury thermometer and ask a pupil to take the readings. (The use of a thermocouple or a thermistor to measure the temperature is too indirect and may confuse an otherwise simple demonstration.)

Procedure

Pour cold water into one bucket until you have 2 kilograms of water. Pour hot water into the other bucket until you have 3 kilograms.



Stir each lot of water and take its temperature. Record the temperature.

Immediately after taking the hot water's temperature pour in the cold water and stir well. Take the final temperature and record it.

Discussion

Ask pupils whether the cold water gained as much in temperature-rise as the hot water lost. Clearly, temperature change is not something that is 'never lost' in an interchange. We have conservation among momentum changes but we do not have conservation among temperature changes. Is there something else that we could see conserved in this interchange? Emphasise the search for 'constancy' as one of the essential activities of science.

If we tried adding TEMPERATURE-CHANGE to quantity of water, measured by its MASS, we should be adding together quite different things, as different as speed and money. The total would not mean much, nor would it be conserved. This would not be a good move in science.

We might try *multiplying* TEMPERATURE-CHANGE by MASS of water. Then we should have the same kind of thing measured in the same arrangement of units, for the cold water's gain and hot water's loss. Is this something that is conserved?

Try the calculation, warning pupils that this is a rough experiment.

* But very difficult experimentally because helium molecules carry heat away very fast to the walls of the container.

† Class Expt 89b Measuring heat

The purpose of this experiment (and of the next one) is to show how heat can be measured with water. Pupils may have learnt this in an earlier year but it is best for them to try it again here unless they are very familiar with it. Our treatment of Conservation of Energy will not make sense if pupils do not, at this point, have a clear feeling for the measurement of heat with water and a thermometer.

Apparatus

8 immersion heaters	item 75
8 transformers	27
8 aluminium containers	76
8 thermometers	542
8 balances‡	206 (or 42)
8 stopclocks (or clock on the wall)	507

‡ If the school already has lever-arm balances they will suffice; but we recommend spring balances for simplicity and easy use.

Pupils work in groups of four.

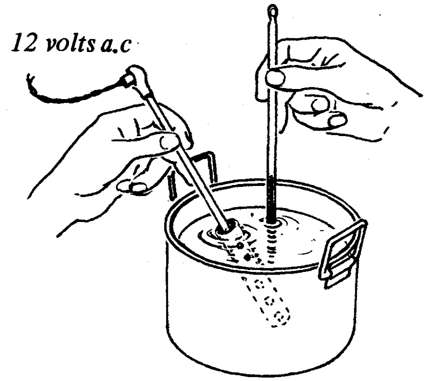
Procedure

Pupils follow these instructions:

* * * * *

Use an immersion heater to give heat to water in a metal saucepan. The heater has a coil of fine wire made of high-resistance alloy. As long as the heater is water-cooled it will work well. But if you run it when it is dry, its coil may overheat and break.

Put 1 kilogram of water in the saucepan. Immerse your heater in the water. Connect it to the 12-volt output of a transformer.



Stir the cold water and take its temperature.

Run the heater for five minutes, stirring the water all the time, using the heater itself as a stirrer.

At the end of five minutes switch the heater off; continue stirring and take the highest temperature.

If you like, repeat the experiment with $\frac{1}{2}$ kilogram of water in the saucepan. You would have to cool the saucepan under the tap first, so that you did not start with warm apparatus that would lose heat unnecessarily quickly.

Calculate how much heat your electric heater gives the water in five minutes. Your answer will be measured in kilograms-of-water × °C. You may call these 'thermal units' if you like. For our discussion of heat and energy we shall presently use a special *temporary* name, 'caloric units'.

* * * * *

† Class Expt 89c Measuring heat by burning alcohol

This experiment is crude but it gives many pupils a feeling of direct measurement of a supply of heat—the little 'spirit lamp' is obviously a miniature furnace. The measurements will be rough and uneven. Pupils will see that what they are measuring is only the heat received by the water—a lot more heat escapes in gases. Mention this and emphasise the idea of the experiment measuring 'useful heat'.

Apparatus

8 aluminium containers	item 76
8 balances	206 (or 42)
8 5-cm^3 beakers	512/4
8 metal supports‡	
methylated spirit, and dipper to dispense 1 cm^3	
8 thermometers	542

‡ The metal support is a strip of thin aluminium or tin plate bent to a rough V-shape to act as a wind shield and to support the saucepan. A strip about 20 cm × 7 cm is suitable.

Pupils work in groups of four.

Procedure

Pupils follow these instructions:

* * * * *

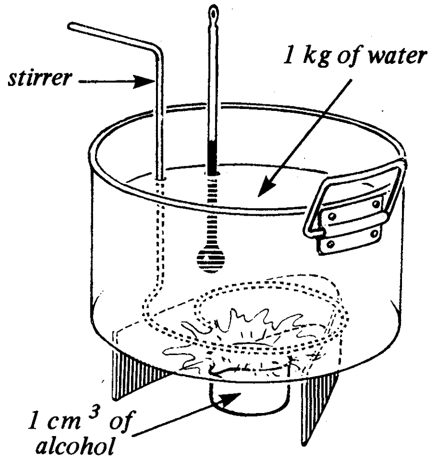
Weigh 1 kilogram of water into the saucepan. Place the saucepan on the metal stand.

Ask for 1 cm^3 of methylated spirit. Your teacher will ladle it into a small beaker.

Stir the cold water and take its temperature. Put the small beaker under the saucepan. Light the alcohol. Let it all burn. Stir the water and take the temperature.

How much heat, measured in thermal units, does that dose of alcohol give to the water?

* * * * *



Note: 1 cm^3 of alcohol burnt fully will yield about 4.5 thermal units to the water. Measurements will range from 3 to 6 but the value of the experiment is in its pattern not in its numerical result.

† Class Expt 89d Estimate the heat given to aluminium

Here we ask pupils to compare the thermal behaviour of aluminium with the thermal behaviour of water—as in the old-fashioned concept of specific heat. Therefore they do not need voltmeter and ammeter measurements for their heater: they simply *compare* this measurement with their earlier measurement of heating water with the same immersion heater.

Apparatus

8 immersion heaters	item 75
8 transformers	27
8 aluminium blocks	77
8 aluminium saucepans	76
8 balances	206 (or 42)
8 thermometers	542
8 stopclocks (or clock on the wall)	507

Pupils work in groups of four.

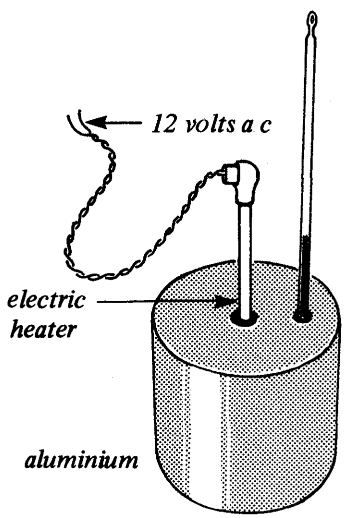
Procedure

Pupils follow these instructions:

* * * * *

Compare the warming-up behaviour of aluminium with the warming-up behaviour of water which you tried just before.

Weigh an aluminium block. Insert the electric heater in the central hole and the thermometer in the other hole. (Put a little oil in with the thermometer, to help it to make better contact in measuring the aluminium's temperature. Do not put oil on the heater: that might lead to damage later on when the heater is out of the block and the oil has dried.)



Take the temperature of the aluminium and record it.

As before, switch the heater on for five minutes. Then switch it off and take the highest temperature that the aluminium reaches.

In your earlier experiment you stirred the water carefully. Otherwise your temperature-measurement would be unreliable, with some of the water hotter and some of the water cooler. You cannot stir the solid aluminium. *Why is this experiment not hopeless?*

Now look at your measurements. You may trust your electric heater to give the same amount of heat to a metal block as to a pan of water. (You pay the same amount of money for the electric supply, whatever the heater is heating.) Try multiplying MASS OF ALUMINIUM by TEMPERATURE-RISE. Is your answer the same as for MASS OF WATER multiplied by TEMPERATURE-RISE in your earlier experiment with the same heater? If so, you have found something interesting, the same for aluminium and water, therefore perhaps worth naming.

If not, you may still want to get the same number from both experiments, because you do know that the heater delivered the same amount of something you pay for in both experiments. You can force your answer for aluminium to agree with water if you multiply by one extra number, a special comparison-number (c-n) for aluminium. Find out what the number is by arithmetic.

* * * * *

Note: In this case pupils only need to arrive at the factor for converting the mass of aluminium to a 'water equivalent'. They only need a number for comparison with water, about 0.22. They do not need to pursue the calculation to a specific heat capacity such as 900 joules/kg°C. And that would be quite unsuitable at this stage because we are only now approaching the 'Court discussion' that will yield 4200 joules/kg°C as the specific heat capacity of water.

(To bring in a voltmeter and an ammeter as an alternative approach would anticipate both the 'Court' and Chapter 12.)

† REVIEW OF ENERGY TEACHING

Explain that we shall go back to early discussions of energy and question them. Pupils should refer to Chapter 5 of *Pupils' Text 4*.

We know how to measure an energy change when a force pushes something along for a measured distance. [FORCE] × [DISTANCE] tells us something very useful; it tells us how much fuel must be used to do that job; it often tells us how much money must be paid for fuel; it tells us something about the job which is inescapable. We cannot get a job done if it involves a force pushing along a measured distance unless we pay for fuel or take some energy from some other store.

We introduced the idea of 'WORK' which measures the amount of energy changed from one form or place to another. WORK measures *energy-transfer*. Our units for WORK are *newton·metres*, which we call *joules*.

QUANTITATIVE DISCUSSIONS OF ENERGY

We then discussed conservation in interchanges between K.E. and P.E.; and now in this chapter we treat the general problem of conservation.

APPROACHING CONSERVATION OF ENERGY

In earlier years we tacitly took Conservation of Energy for granted without pupils (or even ourselves) noticing the assumption; but we should not continue to do so now. If we did, we could not honestly say that the Conservation of Energy is a great principle in our understanding of nature.

In the teaching of other sciences, energy conservation *will probably be assumed throughout*; and that places a stronger moral burden on physics teachers to talk about the experimental basis of our belief. So Chapter 9 in *Pupils' Text 4* invites pupils to read the experimental support for the principle.

EXPERIMENTAL EVIDENCE FOR CONSERVATION

Lines of attack In discussing experimental evidence, we have three lines of attack:

a. Ideal machines have equal input and output of mechanical energy.

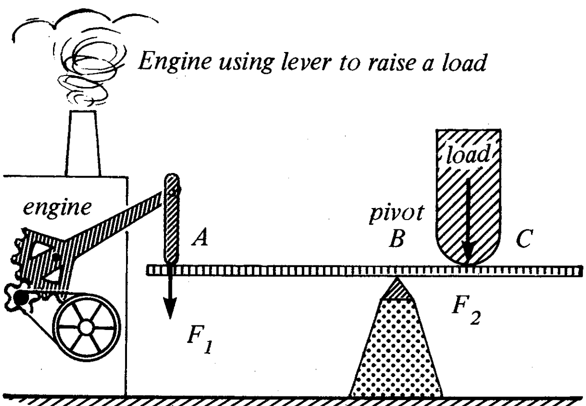
With a real machine the output of mechanical energy is always somewhat less than the input and some heat appears. We are led to suspect that heat may be a form of energy.

b. The total of calculated potential energy and calculated kinetic energy is constant in a conservative(!) system.

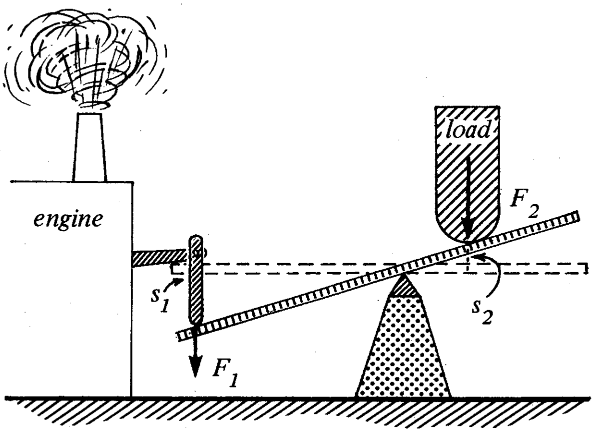
c. We have a sound experimental basis for regarding heat as a form of energy, such that interchanges among kinetic, potential, electrical energy etc. and interchanges between them with heat keep a constant total in a closed system.

How far does each of those lines of attack give the assurance that we owe to our pupils—that we owe to the next generation of the general public?

Comments on those lines Examine each line in turn.

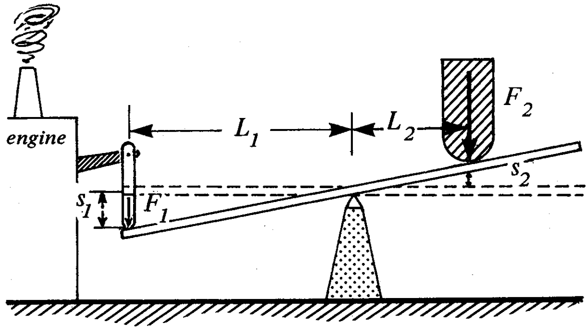


Engine using lever to raise a load

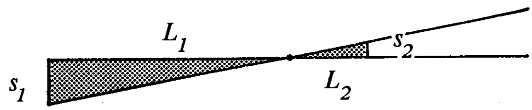


a. Machines We should certainly deal with simple machines; and, for our first look at conservation, we might well treat them in ideal form. We show, by arguing about forces and distances, that a lever does not multiply energy; nor does a pulley system.* No machine ever manufactures energy. No machine puts out more energy than it takes in. Perpetual motion is impossible.

There is a full note on *Perpetual Motion*—in contrast with *Perpetual Movement*—in the *General Introduction* issued with *Teachers' Guide 3*.



By experiment, $F_1L_1 = F_2L_2$



The shaded triangles are similar.

$$\frac{L_1}{L_2} = \frac{s_1}{s_2}; \qquad \therefore \frac{F_2}{F_1} = \frac{L_1}{L_2} = \frac{s_1}{s_2};$$

$$\therefore F_1 \cdot s_1 = F_2 \cdot s_2.$$

Input work = Output work

b. Conservation of (P.E. + K.E.) We mention this but we must not exult over it because we devised $\frac{1}{2}mv^2$ to make that form of conservation true!

We arrived at $\frac{1}{2}mv^2$ by working out the value of FORCE × DISTANCE for a force that is accelerating *m*. But we also calculate changes of P.E. by FORCE × DISTANCE for raising a load or stretching a spring. So we expect to find that kinetic energy $\frac{1}{2}mv^2$ and potential energy are complementary. They add up to a constant total in any conservative system. A conservative system is one in which *the force is the same on the way out as on the way in.*

Example: A stone dropped over the edge of a

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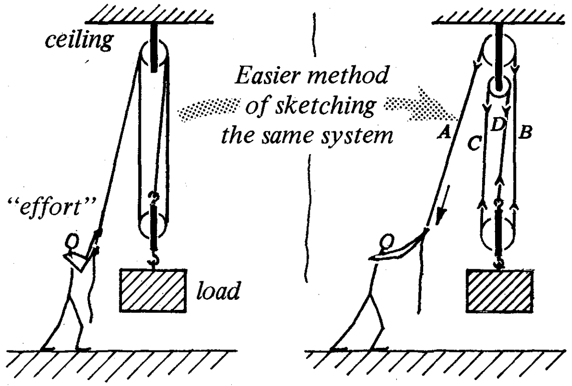
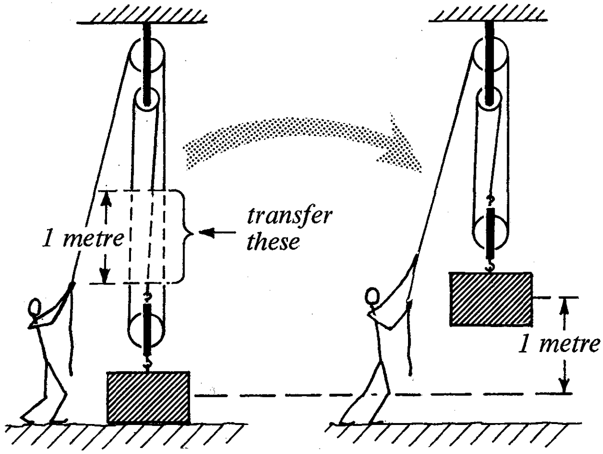
*If pupils never tried simple experiments and arguments concerning INPUT WORK and OUTPUT WORK for a see-saw and then for a set of pulleys, it seems essential to bring in now some quick demonstrations of the experiments in Year 2.



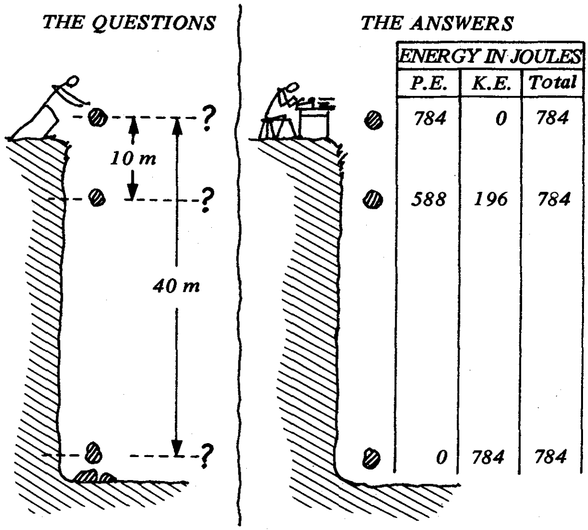
Pulley system: Force ratio



Pulley system: Distance ratio

ROCK (2 kg) IN FREE FALL

(P.E. + K.E.) = ? AT EACH STAGE

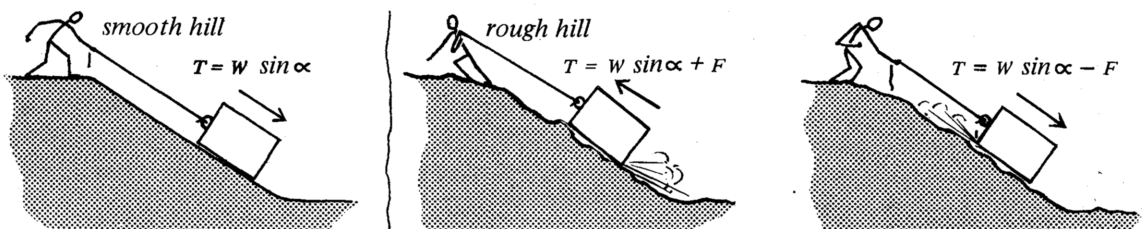


ENERGY IN JOULES		
P.E.	K.E.	Total
784	0	784
588	196	784
0	784	784

cliff starts with a rich store of gravitational potential energy, and it gains more and more kinetic energy. We should not be surprised to find that at all stages of fall (forgetting air friction), the sum of K.E. and P.E. remains the same. There we have a very simple form of Conservation of Energy—of our own manufacture.

Gravity exerts the same pull when the object it acts on is moving downwards as when we are pulling the object upwards. The pull is the same on the way up as on the way down. That characteristic holds for the force we (or some other engine) must apply in pulling against gravity forces and storing up potential energy. The change of potential energy for a given distance moved is the same 'on the way out as on the way in'. We get back from the store all the energy that we put in. And when the energy that we get back is all turned into kinetic energy, we find that the total of K.E. and P.E. remains constant.

However, there are other forces, such as those due to friction, which are not 'the same on the way out as on the way in'. If we pull a load up a rough hill, we increase its potential energy; but we also produce some heat, pulling against friction forces. If we then let the same object move *down* the hill, gravity still pulls downward, and its downhill component is still the same in size and direction as before—so we regain just as much energy from the P.E. store as we put in; but some is diverted by friction. When the object moves downhill, friction turns round and drags uphill against the motion. Some of the energy supplied by the agent that pulled the object uphill went into heat; but that heat does not get reconverted into mechanical energy on the way down. Instead, still



more heat is produced. Then, although all the gravitational potential energy that was stored up is returned, we do not get it all back as kinetic energy: some of it is delivered, inevitably, as heat.

In this case, we cannot say that (P.E. + K.E.) keeps a constant total. Considering the forces, we see that the agent pulling the body uphill has to exert more force than the component of gravity, while on the downward trip the body needs less than that component from any external agent. The external force is not the same on the way down as on the way up.

An easy overall test is to see whether heat is developed.

c. Many forms of energy Any real machine puts out less mechanical energy than it takes in. Does that mean that energy is being destroyed? Is energy conserved in that case, and is it conserved in other more complicated transactions?*

Neither experiments on real machines nor the constancy of [P.E. + K.E.] can provide adequate evidence of conservation. In every practical case heat appears or disappears. When heat or electrical energy or chemical energy is involved, *(a)* and *(b)* are of no avail. So we turn to *(c)* for full support of energy conservation.

We appeal to the great series of nineteenth-century experiments done by Joule and others, in which interchanges of electrical energy, chemical energy, mechanical energy and thermal energy were shown, with increasing certainty, to support a general Conservation of Energy.

Although the result of each measurement was reduced to a numerical value of 'J', these experiments did not just show that HEAT and MECHANICAL ENERGY are interchangeable: they compelled a belief in conservation in a much wider variety of interchanges.

THE EXPERIMENTAL TESTIMONY: 'THE COURT WILL SIT'

In *Pupils' Text 4* we invite pupils to survey this evidence, not as an arbitrarily chosen topic in the history of science, but to show the building of a very important part of science. To support the great generalisation, the many and varied experiments need some description; and then the converging values of 'J' form an exhibit of evidence. So Chapter 9 discusses the history of the work of Joule and others that led to the belief in the Conservation of Energy and still provides the experimental support for the great principle.

If pupils know beforehand that these are pieces of testimony from difficult experiments, pointing to a crucial verdict—a universal constant for 'J' as a symbol for conservation—they will not find this great story confusing.

Necessary clarity If we adopt that policy in teaching, then, *until the case is proved*, we must have a different unit for the thermal measurements (most of them done with water) from that used for the mechanical measurements.

The trouble may be illustrated by a story: 'A murder has been committed. The police believe they have found the culprit. In the trial, the police may not call the defendant "the murderer" before the case is proved.'

Otherwise the testimony in favour of conservation would be given in a series of numbers in the strange units 'joules/joule'; or, worse still, there would be statements like this: 10 000 joules of mechanical energy went in; 8000 joules of thermal energy appeared; and 2000 must have been lost somewhere, probably as escaping heat.

That would make the story confusing as well as lame.

Therefore our plan is to keep some thermal units in use until we have discussed the evidence for general Conservation of Energy.

In preparation, pupils have made thermal measurements with thermometers and water and expressed the results in *temporary* units. Those experiments suffice to give a feeling for 'heat', and prepare for discussion of Conservation of Energy.

TEMPORARY THERMAL UNITS

Our temporary unit based on metric measurements is the heat required to warm up one kilogram of water one degree on the Celsius scale. Until recently, we have all used the name 'kilocalorie' (Calorie) for this.

* As an extreme example consider the case of a bullet that is fired into a suspended target and stays there. We can account for some of the energy clearly. The target rises as it swings back and we say it gains potential energy. But if we calculate the kinetic energy the bullet loses and the potential energy the target gains, we find that the latter is much smaller.

Now scientific societies in many countries have agreed to use a standard set of units (SI) in physics journals and other reports.

Physics teachers and textbook writers have been recommended to extend that agreement on SI units to teaching and books in schools. Strict insistence on a single set of units is very valuable in learned journals throughout the world. But some relaxation from it proves helpful for young pupils.

For example, while a journal might report the measurement of a small length as 1.2×10^{-2} metres to maintain uniformity, a beginner may find it easier to see the width of his or her finger as 1.2 cm, or perhaps 12 mm. In this way, an extension to decimal multiples of the standard SI unit promises to be helpful and harmless in teaching.

Through the best of intentions one recommendation for uniformity has taken quite a different turn. In learned journals the SI system quite rightly asks that energy be given always in *joules* (newton·metres). This applies to thermal energy (heat) as well as all other forms. Therefore the Calorie is not now needed for use in learned journals etc., just as the inch and the gallon and the mile/hour are no longer needed.

However, in the extension of the recommendations to school teaching a new aspect has been attached—accidentally we trust—to one of those changes. The Calorie is regarded not just as unnecessary—soon to be phased out of professional use—but as *improper*. Some teachers, and some educational authorities, have given the Calorie such a strong feeling of impropriety that they consider that even in discussing the historical support for the Conservation of Energy we should not mention Calories in the necessary thermal measurements. Yet, they say, we may quite properly use a kilogram-of-water·°C as a temporary unit.

As a diplomatic compromise, we have tried to use this latter clumsy but explanatory unit for early stages in our present books—sometimes calling it a 'thermal unit'—although we expect many teachers, and pupils too, will call it, for short, a Calorie (or kilocalorie).

So in Chapter 9 of *Pupils' Text 4*, intended for pupils' own reading, we adopt a special temporary name for the thermal unit kilogram-of-water·°C. We call it a 'caloric unit' while we are carrying pupils through the conflict between a Caloric theory of heat as a conserved fluid and the view which we hold, that heat is a form of energy.

At the end of that discussion, when we hope pupils will agree that heat should rank as a proper form of energy, we ask that heat should be measured in joules from then onward.

{The suggestion that we should not mention the Calorie did not come solely from enthusiastic support of the SI system. It also arose, earlier in the history of science teaching, from a strong plea by engineers, and by scientists in other fields, that we should take heat for granted as a form of energy—and no longer get into an unwelcome historical discussion.}

{Each of us concerned with teaching must sympathise with that view when we consider the damage to young people's enthusiasm and understanding that would be wrought by teaching out-of-date history at many points in a programme. We have only to think of our own reaction to an interlude of history in some unfamiliar branch of science which we ourselves are trying to learn. Once pupils—or students at a later age—complain that they are 'being dragged through a study of other people's mistakes', the science which we ourselves love can lose its power and charm.}

{However in constructing the programme of this project we decided that the Conservation of Energy should be offered as a great generalisation emerging from an impressive variety of experimental tests—and we note that some similar teaching projects emphasise historical discussions more often than we do. That is why we offer the special chapter for pupils to read and then judge the evidence.}

Pupils who aim at O-level should read the account of the 'Court' in *Pupils' Text* Chapter 9. And they should try to consider the evidence in the summing-up table with the care of a serious jury.

Teachers who do not wish to spend time on this discussion in a busy year should note that it is offered as an account for pupils' own reading; and therefore any O-level examination question** on it would be framed as a test of such reading.

Other pupils Some less academic pupils prefer clear-cut statements to a discussion of alternative views; and they may learn more science if we do not press the discussion. So, with a wider range of abilities in physics classes, we think teachers may find that only some pupils will enjoy the 'Joule' discussion. We hope teachers will offer it to pupils with the flavour of 'Read this only if you like it; but there is a reward there, of understanding science.'

ILLUSTRATIVE EXPERIMENTS

When pupils are reading Chapter 9 let them try a simple qualitative form of Hirn's experiment of hammering lead. They might also look for tangible heating in a bicycle pump.

Then let pupils try a class experiment with an avalanche of lead shot as a sample 'Joule experiment'—not for a reliable measurement but to give some sympathetic understanding of Joule's skill.

Although physicists are familiar with Joule's paddle-wheel experiment, pupils have no picture of the apparatus and may easily emerge with no clear idea of what it did. Therefore it is worth while to show a model, even if it does not yield any measurable temperature rise. The simplest model of Joule's paddle-wheel apparatus is just an egg-beater driven by hand. Some teachers might like to devise a model nearer to the real apparatus, with a paddle-wheel driven by falling weights; but we do not suggest giving a detailed description or picture of the original apparatus.

† Class Expt 90a Converting mechanical energy to heat

Apparatus

16 hammers
20‡ pieces of thin sheet lead ($5 \times 2.5 \times 0.2$ cm) with handles of heavy iron wire — item 220

‡ The lead may split: spares are needed.

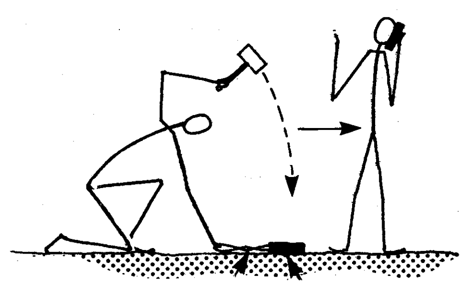
Despite the noise, this is far better as a class experiment than as a demonstration.

Preparation

Bend the iron wire to form a handle at one end and a twisted region at the other to hold the lead. Wrap the lead sheet firmly round it.

Procedure

Each pair of pupils should hammer their lead on the floor or anvil, hammer it violently, then



quickly hold it against a cheek to feel if it has gained heat.

* One teacher reports a pupil saying, 'If you believe it, we will.' This delightful remark epitomises a serious difficulty in modern science teaching. General talk, newspapers, and some of the more traditional teaching besides, have taught pupils to regard science as material knowledge that is issued by authority and should be taken on trust. Although in our programme we shall offer pupils knowledge—which we hope will be trustworthy knowledge—we are just as much concerned with giving them an understanding of the basis of that knowledge and helping them to maintain a critical, questioning attitude. Here, our court trial is no mere historical game: it offers a glimpse of building scientific knowledge.

** This programme of O-level physics differs in many places from a traditional programme in choice of topics and in treatment. Consider our inclusion of cloud-chambers in Years 1, 4 and 5; our use of the fine-beam tube to measure e/m; our omission of hydrostatics and some of statics; and our use of astronomy to show the growth of theory in Year 5.

The examiners of the Nuffield O-level examination have respected those differences. They also respect our special attitudes, such as our development of optics by images, rather than by formal laws; and our view of atomic structure as a series of 'thinking-models'. We consider that an understanding of scientists' belief in energy-conservation ranks among such attitudes. That is too important, in these days, to be replaced by assertions.

Expts 90b Converting mechanical energy to heat *(OPTIONAL)*

The experiments suggested here are much less impressive than the class experiment of hammering lead. They could follow the class experiment but they should not replace it.

Apparatus

for *(i)* electric drill
blunt drill
piece of metal

for *(ii)* bicycle pumps

for *(iii)* egg-beater

Procedure

(i) Bore a piece of metal using a blunt drill. Pass the drill round. Pupils feel it. Or, drill a thick piece of wood: smoke emerges.

(ii) Pupils push the piston of a bicycle pump in quickly while holding a finger on the outlet. They feel the heating.

(iii) To show the kind of arrangement Joule used in his water-churning experiment, hold an egg-beater in a beaker of water and drive it by hand.

Class Expt 91 The 'waterfall' of lead: measurement of 'J'

Apparatus

8 balances‡	item 206 (or 42)
16 cardboard tubes	163
8 kg lead shot ‡‡	
16 plastic or cardboard cups	164
8 thermometers	542
8 metre rules	501
32 corks or bungs to fit tubes	

‡ Balances are not essential but having them available will save anxiety or delay.

‡‡ Each pair of pupils will need about $\frac{1}{2}$ kg of lead shot.

Procedure

Pupils follow these instructions:

* * * * *

Try an experiment like one of Joule's early ones. Instead of Joule's waterfall of water, try a 'waterfall' of lead shot. Let a handful of shot fall from top to bottom of a cardboard tube. Take the temperature of the shot before and after, by pouring it into a light cup and plunging a thermometer gently in among the shot.

What improvements can you make?

When you have found a measurable effect, consult your teacher about measurements and treatment of results.

* * * * *

There are three possible levels of outcome:

(i) Qualitative Pupils just see the small change of temperature. Although this is much less impressive than the result of hammering lead, the experiment is a rough model of a 'Joule experiment' and all pupils should try it.

(ii) Simple measurement of the 'rate of exchange' Pupils expect to need a measurement of mass of lead but they will find it cancels out—ask them why. They do need to know the specific heat capacity of lead, or at least the comparison-number between lead and water. Tell them the latter is about 0.035—and ask them to suggest a reason for choosing lead*. They calculate the number of joules of mechanical energy that disappear to provide one 'caloric unit' (1 kg-of-water·°C).

(iii) A measurement of 'J' such as: 'The specific heat capacity of water is 4200 joules/kg·°C.' That would be jumping to the court's conclusion and would almost certainly confuse pupils' understanding of the court's trial.

* We use lead shot rather than water because of the low specific heat capacity of lead, nearly $\frac{1}{30}$ of that of water. Thus, we expect a temperature rise 30 times as great as with water. We choose lead rather than some other metal because it is inelastic (not springy), so that all the energy of the falling shot turns rapidly into heat as the atoms in the lead are dragged this way and that in the impact of stopping.

Remember that most metals have approximately the same thermal capacity per unit *volume*; so, for some uses, elasticity is the important criterion. Here, however, it is the thermal capacity per unit *mass*, or the specific heat capacity that detemines temperature rise; and we want as large a temperature rise as possible.

CAREFUL MEASUREMENTS OF 'J'?

Since the exchanges between mechanical energy and heat are so important, physics teachers are tempted to ask pupils to measure 'J'; and ingenious devices have been invented for school use. But in our treatment such an experiment could be more upsetting than helpful, so we do not advocate it.

If we do offer pupils a 'good' experiment on the 'mechanical equivalent of heat', we are offering them an interesting, difficult experiment that is also dangerous; there is a danger that they will think the aim of the experiment is to get 'the right answer', 4200 joules per thermal unit. The nearer their result is to that right value, the more contented they will be, and the more they will expect us to call their work very accurate.

In fact, a trustworthy measurement of 'J' is very hard to come by: the work is beset by errors, some known and some unknown. Earlier generations of physicists, aiming at training pupils to follow standard experiments, have with great ingenuity designed apparatus that does give the right result. At worst, look at the simple lead-shot experiment: by choosing the right amount of shot and encouraging pupils to give the right amount of bang to the downward-slung tube, we could produce a surprisingly good result. None of us in teaching physics would dream of doing that; but we may easily be persuaded by someone who has made a more elaborate apparatus that it does provide for a genuine, accurate measurement; and we might eagerly lead our pupils to it, without realising the risk. When some apparatus gives a 'good' result easily and consistently in pupils' hands, that success is more likely to come about through compensating errors than with true accuracy—which, as we know from Joule's work, is hard to attain.

Joule's own increasingly consistent results were obtained by using very small temperature rises and, in most cases, large apparatus. Even then he had to make meticulous allowances for heat losses. In modern professional measurements of 'J' the care in carrying out the experiment will amaze any reader who follows the full published records.

The rough chart on the opposite page shows later measurements converging on a constant value.

TWO CENTURIES OF ENERGY STUDIES

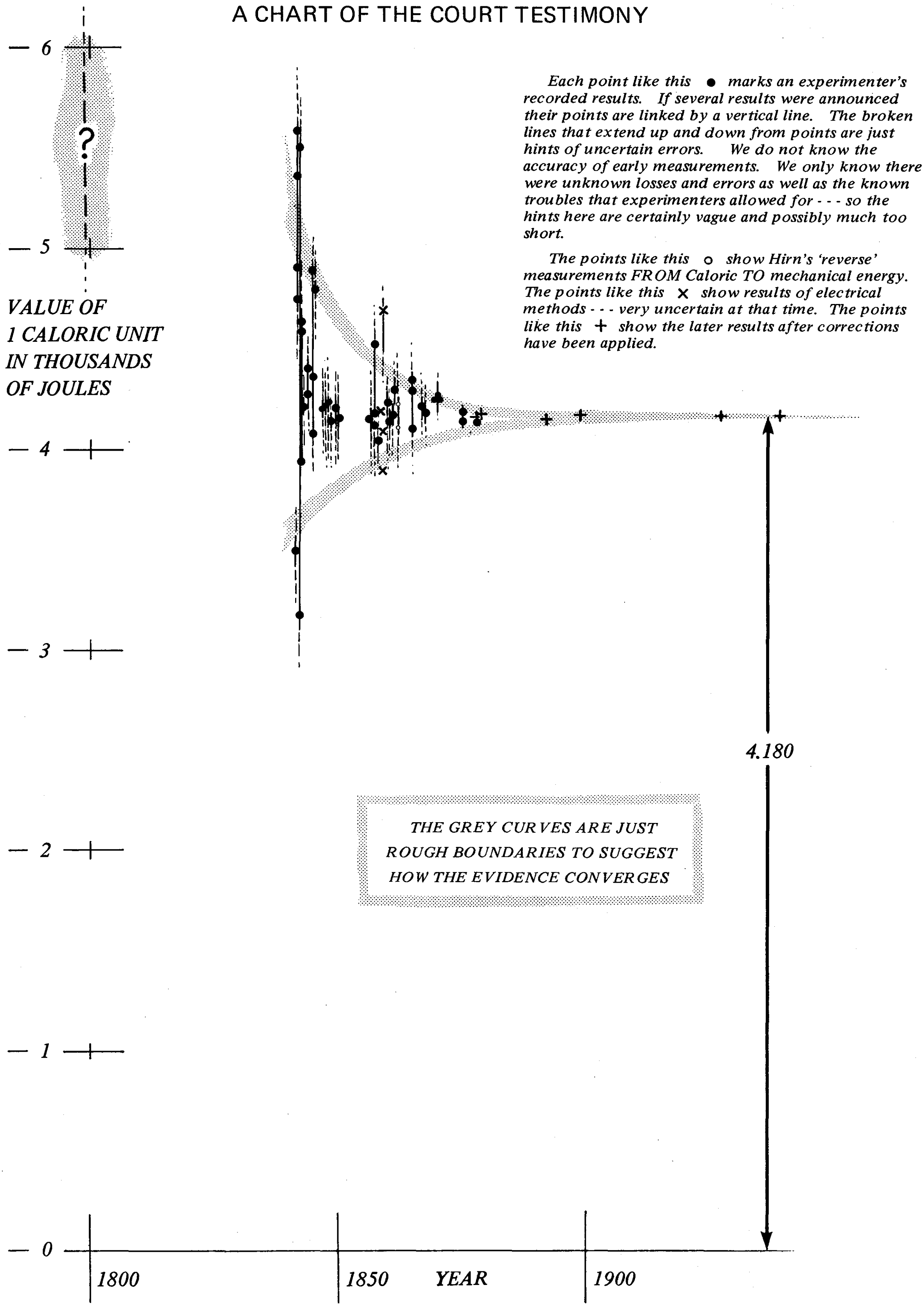
Nineteenth-century physics At the beginning of the last century, energy was an idea without a clear name. In the hands of Joule and many others the scheme of conservation was built up: mechanical energy into heat, and heat to mechanical energy, and the books balanced; chemical energy to heat, or chemical energy to electrical energy and then to heat, or electrical energy to chemical energy and then to heat—all these were tried in a host of measurements that were checked and cross-checked. The books balanced.

It was a tremendous scientific century: at its beginning, chemistry growing to manhood, the electric current just discovered; in the middle, electrical science and engineering making huge strides; and at its end atomic physics just beginning to open up. The Conservation of Energy was perhaps the greatest development of all; it was the conceptual scheme that tied the others together.

Twentieth-century physics Nowadays we find Conservation of Energy so useful that if physicists discovered a case of some energy disappearing without any other form of energy appearing instead, they would probably manufacture an imaginary new form of energy to keep the balance sheet true. This would not be wrong science, provided they always remembered that the new form had been *invented*.

{In fact that was, in a way, done earlier this century when the little particle called the *neutrino* was invented by theoretical physicists. In certain radioactive changes, some of the released energy was unaccounted for; so the neutrino was suggested as a tiny, invisible, perhaps undetectable, particle that carried away the extra energy. At the same time some momentum and some angular momentum were unaccounted for, and the same small particle could be employed to keep the balance of those physical quantities true as well. Therefore, even if it were not real, the neutrino was useful in cataloguing what happened in those nuclear events.}

{Physicists described events in terms of


A CHART OF THE COURT TESTIMONY
Each point like this ● marks an experimenter's recorded results. If several results were announced their points are linked by a vertical line. The broken lines that extend up and down from points are just hints of uncertain errors. We do not know the accuracy of early measurements. We only know there were unknown losses and errors as well as the known troubles that experimenters allowed for - - - so the hints here are certainly vague and possibly much too short.
The points like this o show Hirn's 'reverse' measurements FROM Caloric TO mechanical energy. The points like this × show results of electrical methods - - - very uncertain at that time. The points like this + show the later results after corrections have been applied.
VALUE OF 1 CALORIC UNIT IN THOUSANDS OF JOULES
?
6
5
4
3
2
1
0
4.180
THE GREY CURVES ARE JUST ROUGH BOUNDARIES TO SUGGEST HOW THE EVIDENCE CONVERGES
1800
1850
YEAR
1900

neutrinos as agents quite happily for years without having much hope of ever being able to observe the particle. Since it has no charge and practically no mass, it is a much more evasive creature than the large neutron. In recent years, however, experiments have provided strong evidence for the existence of real neutrinos and we now believe in them as well as using them as an idea.}

{If need arose again we should probably invent one more form of energy or carrier of energy, rather than give up a principle which has proved so valuable. Thus in modern days, Conservation of Energy has changed from being a general principle which we have found by experiment to hold in the natural world, to being a part of, so to speak, the parliamentary constitution of our physical knowledge.}

{We should not discuss this development of the idea of energy with our pupils at this stage. It might mislead them into thinking that we do not really understand energy or that we are not quite sure about Conservation of Energy, or perhaps that we are prepared to tell lies about it. None of these is true.}

THE POSITION NOW

We trust that pupils who have read the converging record in the court trial will agree that they have seen evidence for including heat in the great system of forms of energy which is conserved in a constant total.

From now we expect to measure the thermal energy in joules. When we make a measurement of heat with water we use a standard factor of (approximately) 4200 joules for each kilogram of water warmed up 1 °C.

{**Thermodynamics** We can state a general law: 'Heat and mechanical energy are interchangeable at a fixed rate of exchange'—the First Law of Thermodynamics. In its most general form, it includes such statements as 'Perpetual Motion is impossible'. We have extracted this law from a variety of experiments, but in doing so we took an overall view. We asked: 'How much heat?', 'How much P.E.?'; we did not enquire into detailed mechanism. We did not ask: 'What did the chemicals do in the battery?', 'Are the atoms of hammered lead vibrating?' This overall type of treatment is characteristic of *thermodynamics* in contrast with the approach of *atomic physics* that investigates detailed mechanism before stating general results.}

{A similar overall survey of heat engines yields the Second Law of Thermodynamics: 'Heat does not *of its own accord* flow from cold to hot.' This simple platitude combines with the First Law to produce a powerful theoretical science. Thermodynamics provides the Kelvin scale of temperature, the basic theory of heat engines—from steam turbines to rocket motors—and the basic theory of refrigerators and heat pumps. It provides a great variety of useful predictions—such as a connection between a battery's e.m.f. and its chemistry, or the relation 'radiation flow $\propto T^4$'.}

{The foundation of thermodynamics on overall views makes it extremely powerful; no change of detailed mechanism can upset its conclusions.}

{When molecular details are added, we develop a 'statistical mechanics' which treats the probabilities of chaotic motion and makes new predictions; and recently, when applied to bits of information instead of molecules, it offers to reform communication in theory and in practice.}

CHAPTER 10

POWER AND HUMAN ENERGY

A description of this important concept and measurements of pupils' power

It seems better to discuss power now rather than earlier when it would have interrupted discussion of mechanical and thermal energy. However, certain teachers consider that *power* strikes beginners as a more obvious and useful concept than *energy*; and they advocate teaching power first. We hope that some teachers will experiment with that change of order, perhaps on a second round of teaching Year 4.

We have also placed the discussion of human food and energy in this chapter rather than in Chapter 5, because the data are usually expressed as measurements of power: intake in Calories/day, and now joules/day; use of energy in Calories/min and now in joules/min, or, preferably, joules/second (watts).

POWER

There are many occasions when we want to know how fast energy is being transferred from one form to another; a steam engine using fuel to raise a load; an electric motor driving a sewing machine or a lathe; an immersion heater in a water tank warming up the bath water; sunlight concentrated by mirrors on a boiler to produce steam; a loudspeaker changing electrical energy into sound wave energy; our own body converting chemical energy into mechanical energy and heat.

In each of those cases we may want to know how much energy has been transferred from one form to another in the course of a whole day, so that we know *how much* fuel has been used, or how big a bill we shall have to pay.

But we often ask a different question: *how quickly* is energy being transferred in that process *at any instant*? The latter is called power. We may say that energy and power are related in the same way as litres-of-water are related to a flow from a tap of so many litres-of-water per second.

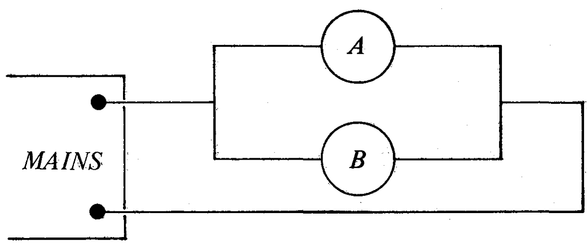
An introductory contrast Show electric light bulbs of different wattages emitting radiation at different rates. The labels on the bulbs will raise the question of the meaning of 'watts'.

Demonstration 92 Comparison of powers of electric lamps

Apparatus

1 25-watt 240 volt mains lamp, preferably clear	item 558
1 60-watt 240 volt mains lamp, preferably clear	559
2 lampholders (BC) on base	162

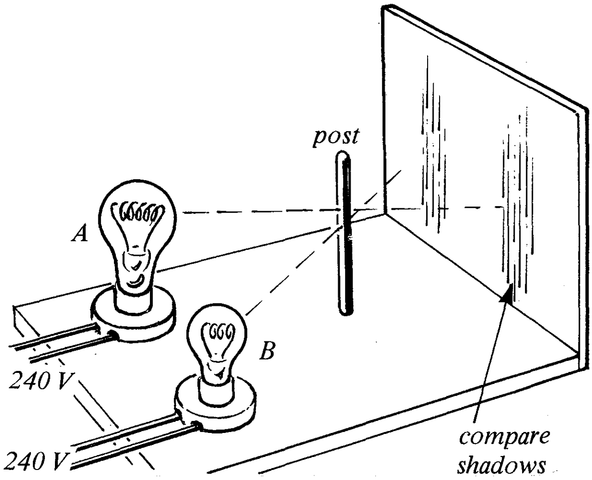
The lamps should be marked clearly 25 W and 60 W.



Procedure

Connect the lamps in parallel to the mains. Switch them on and compare them. Remove them from the holders and hand them round for a look at the markings. Explain that:

One *watt* is just a shorthand word for 1 *joule/sec*.



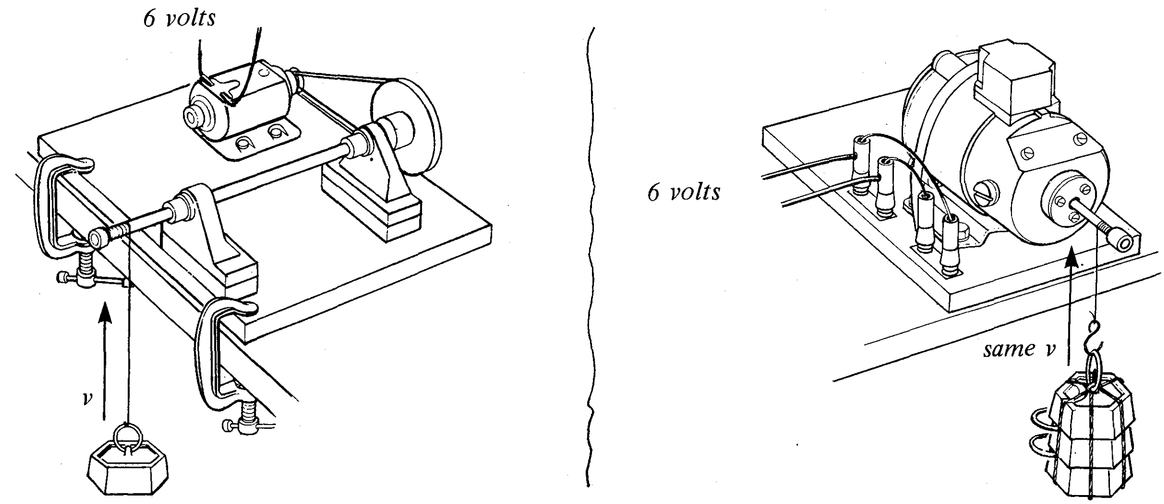
So remember that watts are not units of ENERGY: they are units of POWER. Power tells us how much energy is transferred from one form to another *in each second.*

(The phrase 'rate-of-transferring-energy' seems much harder to beginners. It is wise to avoid it at present or pupils will learn it by heart, carefully, without understanding.)

By now pupils are familiar with joules as 'lumps of energy', and through that will come to grasp the watt as a rate. A mention of *knots* as shorthand for *'nautical miles per hour'* helps pupils to recognise our use of a single word for a rate.

Another contrast: motors Let a toy motor and a larger one each haul up a load. Run each on 6 volts. Give the larger motor a larger load; but arrange things so that the two loads are hauled up equally fast.

Demonstration 93 Comparison of electric motors



Apparatus

1 model electric motor	item 9A
1 fractional horse-power motor	150
1 line shaft	9F
1 L.T. variable voltage supply	59
several 1-kilogram loads	32
string	

Procedure

(i) Small motor Run the motor—(from the Energy Conversion Kit) on 6 volts from the d.c. terminals of the L.T. supply.

Connect its pulley to a larger pulley on the line shaft and let it haul up a kilogram by a string on the line shaft. Pupils note the time it takes to raise the load 1 metre.

(ii) Large motor Let the commercial motor haul up a load of several kilograms at about the same speed.

Run that motor too on 6 volts d.c. (Connect its field coils in parallel with its armature.)

As in the previous comparison of mains lamps, the *voltage* is the same for both motors, but the currents differ, and so do the visible outputs.

Labels on commercial motors reveal the horse-power or wattage. If pupils ask whether those labels give the power that the motor always delivers, at once explain that a motor adjusts itself to its load, and that the power ratings on a motor usually indicate the maximum rate-of-transfer of energy that the motor is built for. If we demand more, the motor will overheat and its efficiency is likely to be smaller.

Animals (including man) have a somewhat similar ability to adjust to the load.

Watts and horse-power Note that many examples of power are non-electrical. A watt is not just an electrical unit. Mechanical engines as well as electric motors are rated in watts or kilowatts.

We still sometimes use horse-power instead as older units; and the word has a good history. Before the time of James Watt himself, railways and coal-mine machinery were run by horses. When Boulton and Watt started offering their early steam engines to mine owners, they met the question: 'If I buy your engine, how many horses will it replace?' So Watt experimented with a London cart-horse raising a load in a mine shaft and decided that

550 foot·pounds-weight per second

was a reasonable estimate for 1 horse-power. We should tell our pupils the equivalent: 1 horse-power = 746 watts. (1 watt may be about 1 rat-power.)

We should spend little time on power, because we can always extend knowledge later. However, pupils should do at least one class experiment.

Pupils' useful power Pupils should time each other climbing a flight of stairs. Every pupil should try this. (Those who have a weak heart should walk upstairs at whatever rate is considered safe; all others should run.)

A very short staircase taken with a flying start will give astounding values of power which are quite misleading from the point of view of food and normal life. To be fair, insist on each pupil running up a long flight of stairs.

(For an adult man, *useful* power output ranges from 75 watts for continuous labour, through 150 watts for short pieces of hard work, to over 750 watts for a short spurt. Children will probably show smaller values of power for climbing—because they have to raise their own smaller weight at about the same speed.)

Efficiency of human beings We tell pupils that when they convert chemical energy into mechanical energy the human muscle system does not do that with complete efficiency, but converts still more chemical energy into waste heat.

At best, the human body working fast is about 25% efficient for doing mechanical jobs. For every 1400 joules of useful energy our muscles transfer, they also produce three times that, about 4200 joules, as waste heat.

Thermodynamic treatment shows that muscles *could* be more than 70% efficient in transferring their chemical energy to useful mechanical forms, but only if the action were conducted infinitely slowly. For rapid action, 25% seems to be the maximum.

So when the pupil estimates the useful transfer from his chemical energy to useful mechanical potential energy by climbing stairs for an 8-hour day, he should multiply that by 4 to find the *total* demand on his food.

Class Expt 94 Pupils measure their own useful power

Apparatus

16 stopwatches	item 507
metre rules or a tape measure	501

Procedure

Each pupil in turn runs up a flight of stairs. Pupils follow these instructions.

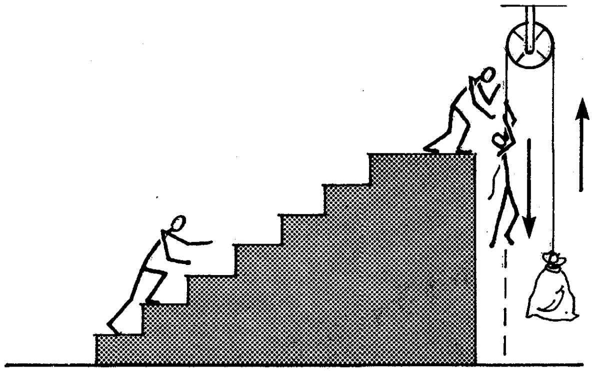
* * * * *

Run upstairs as fast as you can, if possible up many flights of stairs in succession. Ask a partner to measure the time you take.

(If you have a weak heart, you should not run upstairs as fast as you can, but you may still do the next experiment, which all should try.)

Measure the height you have climbed (in metres). Calculate your gain of useful gravitational potential energy (in joules) and divide by the time you took to gain it. That is your *useful* power.

We call the gravitational P.E. that you gain 'useful', because when you have climbed to the top of the stairs you could hold a rope that runs over a pulley to a load that almost balances you and then let your weight raise that load as you fall slowly down to ground level.



But there is also some useless power, because you develop waste heat. Assume that your body is at its best, 25% efficient for rapid motion like this. Calculate your *useless* POWER in that climbing—the power that went into warming you up.

Then calculate your *total* POWER: the rate at which you must have converted food energy to useful P.E. and waste heat together. Express that in watts (= joules per second) and in kilowatts.

For fun, also put your total power in the old units, horsepower (1 HP = 746 watts $\approx \frac{3}{4}$ kilowatt). How many useful HP were you worth?

* * * * *

We should let pupils carry out a further study: repeat the climb at a rate which they consider they would be prepared to maintain if they were obliged to continue for an 8-hour working day. This will give them some indication of the power involved in a steady, medium manual job. Although we live in a civilisation where the push-button-controlled electric motor is replacing human muscles more and more, there are still many parts of the World where human muscles do most of the jobs.

We hope to give pupils a feeling for the necessity of sufficient food. They will not learn that so well by lectures as by trying their own experiment. The next experiment will lead to considerable calculations—but we believe they are worth while in terms of World needs.

Class Expt 95 Pupils measure useful power for an all-day job

Apparatus

16 stopwatches	item 507
metre rules	501

Procedure

Pupils follow these instructions (just after doing Expt 94):

* * * * *

Now suppose you had to go on climbing stairs all day, to earn your living. You certainly could not go on running upstairs like that. Time yourself climbing stairs very slowly and deliberately, as if you were carrying a load on your back. Climb as you would if you had to climb all through a working day of 8 hours. Calculate your useful power, in watts.

The *useful* power of a large horse was measured and found to be about 746 watts. The *useful* power of a human adult, working for many hours a day at jobs like hauling loads up with a pulley and rope, has often been measured. The average is about 90 watts. Compare *your own* useful power with that.

When you know your *useful* power, from the slow stair-climbing experiment, add three times that for waste-heat-production in your muscles.

Then multiply by 60 to find your total output of useful energy in 60 seconds. Multiply by 60 again to find your output of total energy in one hour.

Multiply by 8 to find your total output of useful energy in an 8-hour working day, supposing you kept up your slow stair-climbing all that time.

That is the energy you would need from your day's food, to do that job. The remainder of the 24 hours, you might be resting, because you would be quite tired, and sleeping some of the time. Even resting and sleeping would need some energy, to keep your heart working and your breathing going and your body warm, probably about, 6 000 000 joules for 24 hours. Add that to your cost, in joules, for a day's work and find the total energy you would need to get from food.

* * * * *

Remind pupils that different foods supply quite different amounts of energy from each kilogram eaten and digested.

Pupils' Text discusses food and energy, gives a table of energy values and man's needs. It appeals for the sympathy which must be felt by all who believe in the Conservation of Energy.

Diet *Pupils' Text* has a table of energy needs and food values.

Pupils may know a person who is on a diet that is specified in Calories (or our thermal units). Although we do not now use the Calorie as a unit in physics, we include an alternative listing of food values in old units, Calories per ounce.

If pupils know an adult who is keeping to a diet which provides less than 2000 thermal units a day, they may ask how it is possible for that person to do any manual work without breaking Conservation of Energy. The answer is that there are only three possibilities:

1. the person is not doing any manual work, but is spending a lot of time resting and keeping warm with plenty of blankets or sitting near a fire;

2. the person *is* doing manual work and is drawing for his needed energy on extra stores of fat which can be burnt as fuel;

3. the person is really eating much more than he claims, by eating sweets, etc., which 'don't count'.

We may turn from that to a word about the people in large sections of the world whose diet provides less than 8.4 million joules a day (2000 thermal units a day). Even in hot climates where little fuel is needed to keep man's body warm, we cannot expect heavy manual labour on such a diet; such people are not lazy but unfortunate.

FURTHER DISCUSSION OF ENERGY

Energy box Bring out the 'forces box' with new labels. The string that enables a pupil to feel 1 newton can be pulled out 1 metre. It should now have an additional label 'TRANSFER 1 JOULE'.

This box, which sounds like a mere toy, is in fact a valuable teaching tool which we should keep available in the laboratory for several weeks.

Remind pupils that to transfer 1 *watt* of POWER that could be *useful*, they would have to pull the '1 joule' string all the way out *once every second*.

Details of energy-transfer box

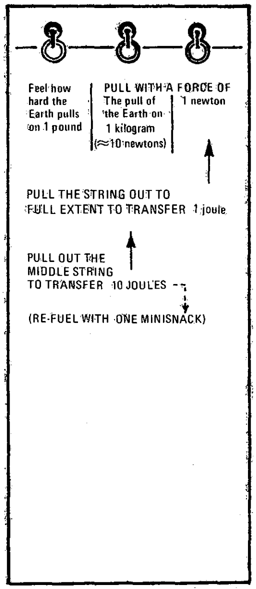
BOX This is the forces box, brought out again with additional labels.

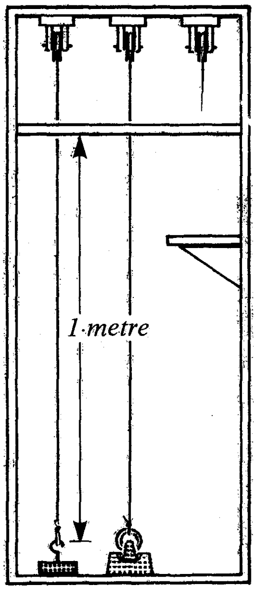
LABELS The forces label runs (in revised form):
PULL WITH A FORCE OF
(a) 1 NEWTON
(b) THE PULL OF THE EARTH ON 1 KILOGRAM ($\approx$ 10 NEWTONS)
(c) FEEL HOW HARD THE EARTH PULLS ON 1 POUND

The new label runs:
(a) PULL THE STRING OUT TO FULL EXTENT TO TRANSFER 1 JOULE
(b) PULL OUT THE MIDDLE STRING TO TRANSFER 10 JOULES (RE-FUEL WITH 1 MINISNACK)

LOADS must be 102 grams and 1 kilogram with the shelf inside arranged to allow each load to rise 1 metre.

THE BACK OF THE BOX should be open so that pupils can go round and look at the arrangement. It would be a pity to make this a 'black box'.





* Some teachers may like to retain the 1-pound load of the earlier model, giving it the new label. Others may prefer to remove it completely.

Class Expt 96 Energy-transfer box

Apparatus

1 forces demonstration box	item 63
2 G-clamps	44/1

Preparation

Make sure the string for 1 joule has the right length to allow the ring to be pulled out 1 metre. Add the energy-transfer label.

Procedure

Clamp the box firmly to a bench and leave it there. Pupils follow these instructions.

* * * * *

To get a feeling for a joule of energy-transfer from your food energy in muscles to another form, pull the cord marked '1 joule' on a forces-and-energy box. Inside the box the cord pulls a load of 0.102 kilogram up through a vertical height 1 metre.

Then the *work* involved is:
(0.102 kg) × (9.8 newtons/kilogram) × (1 metre)
= (1 newton) × (1 metre) of transfer *FROM* chemical energy (in muscles) *TO* gravitational P.E. That transfer is just 1 *newton·metre*, which we call 1 *joule*.

Each time you pull the cord out 1 metre, the transfer to gravitational potential energy is 1 joule; but your muscles are not very efficient engines. They use much more chemical fuel than is needed for the actual job, and convert the rest of the energy released from the fuel into heat. At their best, they are 25% efficient for rapid motion like that. So while you provide 1 joule of gravitational energy which could be useful, you also manufacture about 3 joules of heat which warms your arms and is later wasted to the air. For complete refuelling after one pull, you need one 'minisnack'*.

* * * * *

The box should remain available for some weeks.

* *Pupils' Text* describes the minisnack, a teaching device invented for the *extra* chapter on Energy in *Pupils' Text 3.*

Working against a band brake
(OPTIONAL)

If the laboratory has a wheel with a band brake against which pupils can work, bring it into use. Let pupils measure power at which they can convert their chemical energy to mechanical energy in the wheel which is in turn converted to waste heat in the band brake.

Expt 97 Band brake
(OPTIONAL)

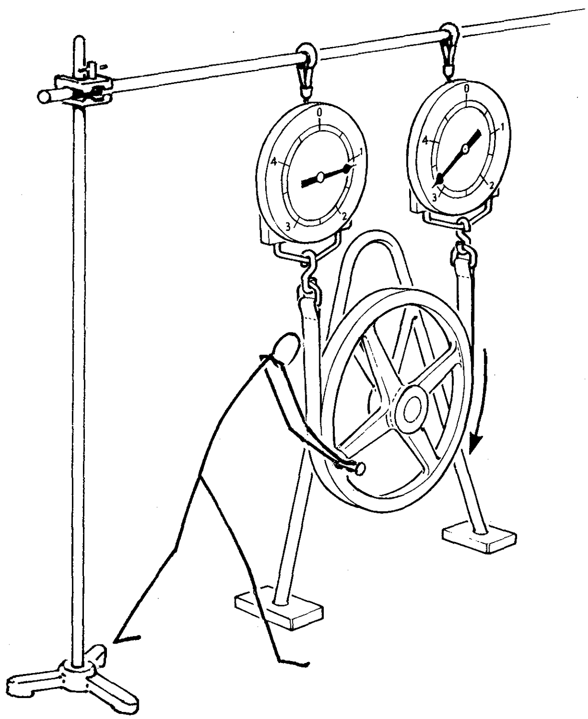
This is useful as a buffer experiment if the apparatus is available.

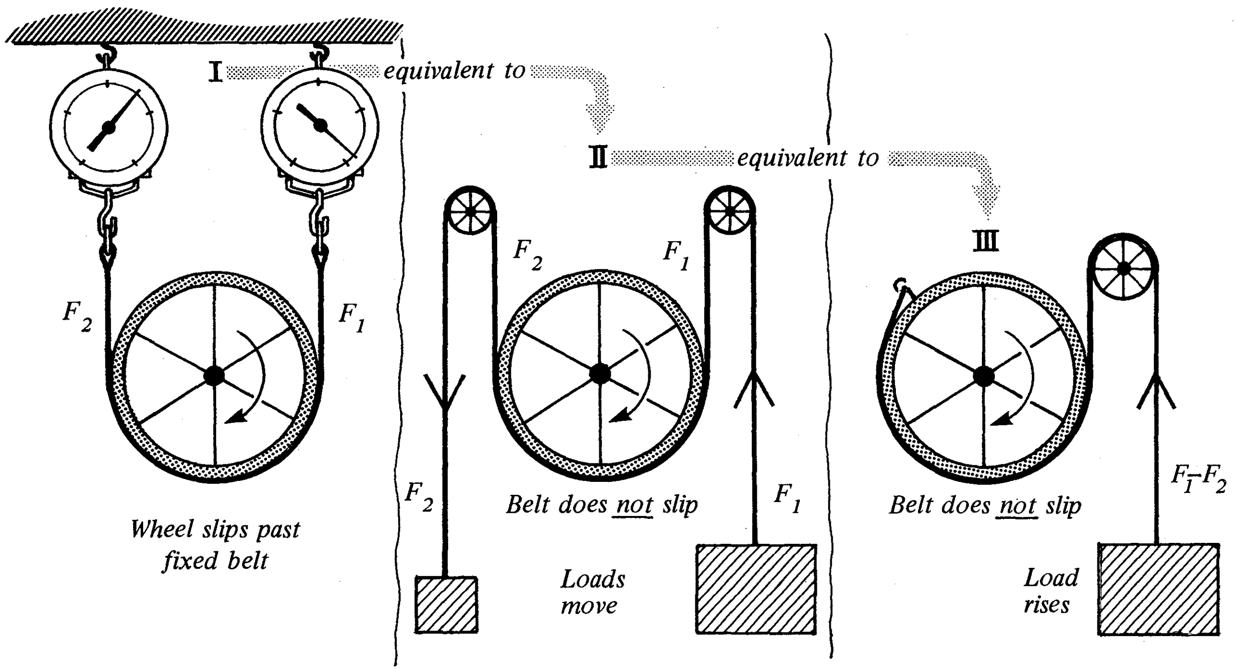
Apparatus

1 wheel with band brake	
2 spring balances‡	
1 stopwatch	item 507

‡ The balances should if possible be marked in newtons. A range of 0 to 100 or of 0 to 200 newtons would do well; but item 212 (0 to 50 N) would just suffice.

The wheel with band brake can be improvised if the lab has a whirling table. Slip the belt off and substitute a belt of webbing or rope. Or a 'bicycle ergometer' could be used; that is, the same thing on a stationary bicycle frame.





Preparation

Secure the belt or rope firmly at the ends of the two spring balances, which are supported from above.

Adjust the belt tension by raising or lowering the support so that both balances read about half full scale.

Procedure

A pupil turns the wheel by hand for at least 30 seconds counting the number of turns he makes. A partner records the average readings of the two balances during the run, and the time taken.

Calculation

This raises questions over calculating the work where the belt slips on the rim of the wheel. We have to convince pupils that

$$\begin{bmatrix}\text{difference}\\ \text{of tensions}\end{bmatrix} \times \begin{bmatrix}\text{circumference}\\ \text{of wheel}\end{bmatrix} \times \begin{bmatrix}\text{number of}\\ \text{revolutions}\end{bmatrix}$$

tells us the work. Some pupils find that easy to understand when we change it to a story of a load (whose weight is the difference between the tensions) being hauled up from a well by a rope which is winding up on the circumference of the wheel. Others find the whole idea very difficult; and for them we should omit it. (An alternative in which the wheel raises a load is easier to understand; but that needs a deep well, or else the imagination to convert it as above to a belt with two loads.) See *Pupils' Text*.

Optional home experiment 98 Output of power cycling up a hill

Make an offer to pupils:

* * * * *

If you like, estimate your own (useful) power when bicycling up a hill. Think out the measurements you would need.

* * * * *

Kilowatt hours Pupils should make simple calculations of the number of joules concerned in certain transfers before kilowatt-hours are introduced. Mention a kilowatt as a useful unit for a big flow-rate of 1000 watts; and then mention kilowatt·hours as units of energy.

That may seem to be going backwards in the evolution of units but kilowatt·hours are too common and too important to be neglected. Yet we should not labour them. If we have been careful with units throughout the course kilowatt·hours will practically look after themselves.

Electrical power Later in this Year, pupils should use voltmeter and ammeter in measuring the power at which an electric lamp transfers electrical energy to heat and radiation. They should also make a measurement on an electric motor. But that must wait for Chapter 13.

THE FATE OF ENERGY

Heat: used and unused Most of the fuels that we use release their stored energy in the form of heat. We can use that heat to do a job such as raising a load, by giving the heat to a steam engine; but after we have got the job done we notice that there is a good deal of heat left unused. Cars and power stations need cooling systems to get rid of waste heat; and aeroplanes lose a lot of heat, though they do not have to make special arrangements for it to be carried away.

Although we find that in every case of change from heat energy to mechanical energy one thermal unit provides 4200 joules of mechanical energy, we also find *we can change only a fraction of the heat that the rule provides into useful mechanical form.* A heat engine's efficiency is limited. There is a tendency for energy-changes to be lopsided, with some of the heat energy from the high-temperature furnace running down to low-temperature heat. Low-temperature heat is not so useful: a kettle of boiling water can run a steam engine; but emptied into a tub of cold water, it will only provide a tepid bath which, if it could run an engine at all, would do so only with far lower efficiency.

{At this point it is good to confer with chemistry colleagues who now distinguish strongly in their teaching between 'thermal energy' and 'free energy'.}

Final form Ask again about the fate of the chemical energy stored in the petrol (+oxygen) used by a small aeroplane that leaves the ground and goes on a flight and returns to the starting point—or a car that makes a similar trip on the roads. Ultimately, all the chemical energy that is transferred becomes heat. It is strange to think that the whole fuel-burning business of a vast system of airways ends up by making the Earth's atmosphere slightly warmer.

WHY DO WE GET TIRED WHEN HOLDING A LOAD AT REST?

A private note to teachers When we think of food providing energy for a useful job, we may wonder about getting tired when we simply hold a heavy load at rest in our hands. That certainly fatigues us and it certainly draws upon some food energy—which ultimately appears as waste heat. Yet we are not obviously delivering any potential energy.

Pupils may ask about this*: 'If I carry a heavy suitcase from the bottom of a building to the top, it gains some potential energy, and that costs me some chemical energy from my muscles. But if I just hold the heavy suitcase up above my head and do not move, I also get tired and I must be using some food energy. How does that happen, when my arms are not moving, so there is FORCE but no FORCE × DISTANCE?'

In answer, we need to describe two quite separate effects: the feeling of fatigue when we maintain muscles in tension and the continuing demand for food energy.

The feeling of fatigue is chiefly produced as follows. When we keep muscles tense, they squeeze the blood vessels and diminish the blood flow. As a result, chemical products of muscular activity accumulate and are not washed away so quickly by blood. This accumulation of chemical products makes the nerves give a sense of fatigue. So the *feeling of fatigue* is chiefly an *indirect result of the muscle tension.*

The continuing demand of chemical energy while we hold a load at rest arises from the mechanism of muscular action. The fibres of the muscle develop tension very rapidly, drawing upon chemical energy. In a large muscle, fibre after fibre is fired into tension as a nerve impulse arrives, but each fibre soon relaxes; and later on it renews the tension in turn, again drawing on chemical energy. When a fibre relaxes, the energy that is released is not returned to chemical energy but only to heat.

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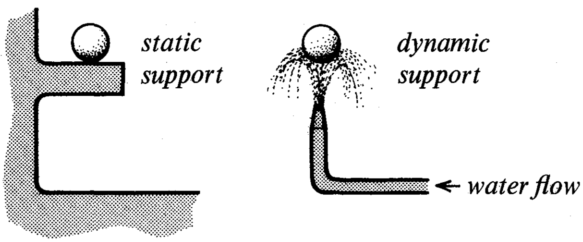
*We offer an explanation here rather than in *Pupils' Text* because the need for it depends on the interests of the class and to some pupils the whole matter would seem confusing—the splitting of an unseen hair.

So the steady pull of the muscle is really the smoothed resultant of many brief tugs. We might call this a 'dynamic' force, like the force made by air molecules* bombarding the walls of their container, in contrast with a 'static' force such as the pull of a stretched steel spring—though even the latter might appear to be the sum of innumerable pulses of tension if we went into atomic detail.



Thus, a muscle supporting a load is not like a static shelf supporting a book but more like a vertical jet of water supporting a ball with a dynamic force. As with the jet, there is a continual conversion of energy into heat; and, as with the jet and ball the muscle can respond amazingly quickly to commands.

Because the fibres cannot reverse the chemical changes of contraction when they relax, there is a continual output of heat from a tensed muscle. This output of *waste* heat increases surprisingly little when the muscle is made to do external work as well.

The sum total of these pulses of force, the overall pull of the muscle, shows tiny statistical fluctuations, like a slight trembling effect. Some observers say they can hear that trembling of jaw muscles if they clench their teeth and listen with ears closed by fingers.

Therefore holding a heavy load does *take* some chemical energy from us. However, we do not have to support the load that way; we can put it on a high shelf and leave it there. The shelf does not tremble (apart from a still more minute Brownian motion, which is reversible). The shelf does not deliver heat. The shelf does not need any fuel to do its supporting. Here is a very useful criterion: can we replace the man or horse or electrical device by some inanimate prop which does not need fuel?

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* The pounding molecules of gas never experience fatigue because at each impact they bring heat energy in and carry it out again as heat!

SECTION IV
ELECTRICITY

This section continues the work on Electricity that started in Year 2 and continued in Year 3. That earlier work was chiefly concerned with simple circuits, effects of currents, electro-magnets, and a first look at electromagnetic induction. Pupils explored phenomena in their own class experiments, which we hoped would give them a sense of personal possession of knowledge.

In this Year, pupils use a voltmeter with a quantitative meaning for measurements of potential difference. They look at, and use, current:voltage relationships, with Ohm's Law as a simple beginning; and they explore transfers of energy and power in electric circuits.

In Year 5, pupils will take up electromagnetic induction again, and learn more about a.c. (transformers, power lines, and use of oscilloscopes). And pupils will use electrical knowledge—from Years 2, 3, 4 and 5—in looking at atomic models both in theory and in experimental illustrations. Their own measurement of e/m for electrons will contribute; and our teaching will also rely on an understanding of Millikan's experiment which pupils meet in Year 4.

In this Year 4, Chapter 11 offers a few quick demonstrations of circuits, for catching-up; then it describes voltmeters and voltage. A quantitative description of potential difference emerges. We distinguish between p.d. and e.m.f. There is a short study of capacitors to show that 'static' charges are the same kind of thing as the charges that move in currents. We mention the use of an oscilloscope as a voltmeter; and we suggest that pupils should try other experiments with that modern instrument, now or in Year 5.

Chapter 12 deals with current:voltage relationships for a variety of devices, wires that obey Ohm's Law, . . . melting glass, molten salt . . . transistors. Pupils also measure some resistances.

Chapter 13 deals with energy and power in electric circuits: measurements for lamps and motors, and estimates of efficiency. The model power line is offered again here, with measurements of useful power and wastage; but the a.c. power line is postponed to Year 5.

Chapter 14 deals with electron streams—preparing for measurement of e/m in Year 5—and electrons and ions in gases. Then Millikan's experiment is described and the Nuffield film of it is offered as one of our most important contributions to atomic knowledge.

CHAPTER 11

ELECTRIC CIRCUITS WITH VOLTMETERS

ELECTRIC CURRENTS

P.D. AND VOLTMETERS DISCUSSION OF APPROACH

We return to electric circuits. Now that pupils are well equipped to deal with energy-changes, we describe potential difference clearly as energy-transfer per unit charge; and we define a *volt* as a *joule per coulomb*.

That is a direct, definite, fruitful way of dealing with p.d. To some teachers it is the way they have always used; but others may find it unfamiliar and wish they could use a more descriptive approach. Yet we recommend this approach strongly because it provides clear teaching of power and energy in electric circuits.

{In modern formal treatment of Electricity, unit current is chosen as the fundamental quantity, defined in terms of the force between parallel currents and resistance is a useful derived quantity, a secondary standard that can be preserved and copied easily. The unit of potential difference is derived from the fundamental unit of current and the unit of power. Officially, one *volt* is one *watt per amp*. However convenient that scheme may be in advanced study and research, it leaves the nature of potential difference itself with only an indirect *description*. Young pupils will find voltage a mysterious concept—at best vaguely described as an electrical pressure—if they are taught that it is something calculated by dividing power by current. And when we extend our use of potential difference to cases where there *is* no current it would remain very puzzling.}

{There is a danger here of confusion in policy between different purposes in building electrical knowledge. There is the matter of careful definition of fundamental units and the deriving of secondary units—that is a matter for professionals and specialists, which should not concern us heavily here. There is the matter of describing and defining the physical quantities to be measured in those units. There we need to know a *physical relationship*, which we extract from experiment, such as [heat] varies as [current^2], or, [rate of copper plating] varies as [current]. We need *operational* definitions—in the technical sense of that word—which describe our scheme of measurement in terms of actual apparatus that could be used.}

{In earlier days, scientists sometimes used concepts that could not be given an operational definition—for example, a precise position for an electron on a sharply defined orbit. Nowadays, we are more careful and try to define, or at least describe, our concepts of physical quantities in terms of possible, or at least conceivable, methods of measuring them. That operational approach, as it is called, has been popular; yet even its most distinguished advocates escape from its bonds for some of their best work.}

{Operational definitions should yield a clear knowledge of the *concept*; but they do not always lead to the most convenient *unit* in which to measure the physical quantity. The unit may be defined quite separately; we often find that it has been chosen earlier in the history of the subject.}

{There is no logical objection to defining unit current in terms of mass of copper deposited per second in electrolysis, while we define our system of current measurement in terms of the force between wires or coils carrying currents. That may sound unnecessarily complicated, but we can lessen any feeling of uneasiness by paying less attention to the unit itself and treating it as something already given us by earlier generations.}

In the present teaching we suggest that teachers should deviate from modern professional practice, and describe current as a flow of charge, measured in coulombs. We then describe and define a coulomb in terms of copper plating.

We can even state our unit current, one amp—meaning one coulomb per second—in terms of copper plating: (0.000 000 329 kilogram of copper carried across every second, in a copper plating bath). Although that does not agree with the standard methods of defining currents by forces, it gives pupils a much easier way of picturing currents. They already have, from common knowledge, a strong feeling for currents as streams of little electrons; and if we bunch those electrons into large coulombs of charge, we can persuade pupils to think of CURRENT being measured in *coulombs per second*.

Again, we find it easier to treat potential difference as a basic, measurable, quantity, described as energy-transfer, *FROM* electrical energy *TO* heat, etc. for each coulomb that passes through the region in question. It is, of course, unscientific fantasy to picture coulombs carrying loads of energy on their backs and disgorging some of that load in each part of the circuit—then gathering a fresh load each time they pass through the battery. Yet if we warn pupils from time to time that such a picture is artificial and has unrealistic details, they can use it to develop a clear working knowledge of potential difference and energy relationships in circuits.

Then resistance keeps its secondary place as [POTENTIAL DIFFERENCE]/[CURRENT] with one *ohm* described as a name for one *volt/amp*—as we may say to pupils 'just dictionary work'.

From our descriptions and definitions of potential difference and current, it follows that [POTENTIAL DIFFERENCE] × [CURRENT] gives the power, the rate at which electrical energy is changed to some other form, such as heat or mechanical energy—we are back to the official definition of a volt.

Then in slang terms 'volts times amps = watts'. And when we generate an e.m.f. we can give a clear description of an e.m.f. as the energy-transfer per coulomb *FROM* mechanical or chemical form *TO* electrical form.

The following discussion describes the kind of teaching we suggest.

Before dealing with volts and voltmeters we give pupils a clear understanding of coulombs. Some pupils will not have met this unit of charge at all; others might have met a description in Year 3.

Coulombs and amperes Talk of coulombs as the things that go round the circuit, things that we might count as they flow past any points we choose on the circuit. We count *coulombs per second* and call them *amps*, much as a policeman might count *cars per minute* for traffic flow, or a hydraulic engineer *litres per minute* for water flow.

If pupils ask us how we know the size of a coulomb, the best reply at the moment is that we read the ammeter, which tells us the rate at which coulombs are passing, and multiply by the time in seconds. That puts the blame for definition on the ampere. And the ampere, we may say for the moment, is defined by the reading of a standard ammeter kept at some standardising laboratory in each country of the world. Pupils already know how one ammeter can be compared with another and that in turn with a standard ammeter.

{Worries about absolute standards and units belong in A-Level or later and not now. Both we and our pupils accept the metre and the kilogram as well-understood units, when they are no more than copies of some chosen standard. We may just as well do the same with the ampere.}

{In A-Level, we can define one amp as that current which when flowing in each of two parallel wires one metre apart produces a force of 2×10^{-7} newtons on each metre of either wire. That definition has two virtues: it reduces the number of *arbitrary* standards that we have to maintain, and it enables us to carry out some important calculations; e.g. the force on a current-carrying coil placed near another current-carrying coil. However, our pupils at their present stage could not carry out those calculations and they are not worried about the number of absolute standards that we use in their physics—nor should we worry them.}

Coulombs and electrons Pupils may ask if a coulomb is the same kind of thing as an electron. We might say that we think of the electron as a very tiny particle, which has a mass like other pieces of matter, but it also carries an electric charge. A coulomb is the charge of a vast collection of electrons. In fact, we can measure experimentally the size of an electron charge in coulombs—that means comparing the two sizes, one electron charge and one coulomb. We shall describe that experiment—Millikan's experiment—soon and pupils might have the result now:

one electron charge $= 1.60 \times 10^{-19}$ coulomb

That comparison tells us that one coulomb is about 6×10^{18} electron charges.

A coulomb is *always* 6×10^{18} electron charges, but in many cases of currents—in conducting solutions, in gases, and in some semi-conductors—some of those charges are negative and are moving one way, and the rest are effectively positive and are moving the opposite way.

{If we were beginning the development of the science of Electricity all over again in the twentieth century, we might well take the electron charge as our basic unit,* instead of the coulomb. But, as we might explain to pupils who ask, electrical science and engineering are too well established for us to make that change comfortably now. (Also the electron charge would prove far too small for convenient use in many practical applications.)}

Coulombs in circuits The essential need here is to let pupils picture electricity drifting past each point in the circuit as nimble electrons or pieces of charge, or a stream of 'electric juice', or what you will—but measured in chunks called coulombs. Instead of saying *what* things are travelling in a circuit—electrons, or electric charges—at this stage, emphasise a cruder view, just saying something that we call electric charge travels, and we measure it in chunks called coulombs. Coulombs travel along a wire in a circuit and we can count them as they go by with an ammeter and a clock.

Voltage and energy Pupils need to be equally confident in expressing some energy changes in joules per coulomb. We can price oranges in pence per dozen, or milk in pence per litre; and we know quite well what kind of things a dozen and a litre are. So it will help to make a coulomb almost too real, by tracing it round the circuit, pushed by the coulomb behind it and pushing the coulomb in front (by means of electrostatic fields), slipping smoothly through a low resistance, banging its way through a high resistance, pushing against the edges of the armature-wires in a motor, carrying the material of chemical ions across with it in electrolysis—always paying out joules as it goes.

Practice Even before a clear feeling for coulombs is established, describe the current measurements in terms of coulombs. Say, 'A current of 2 amps means that 2 coulombs of electricity (or charge) pass each point in the circuit every second.'

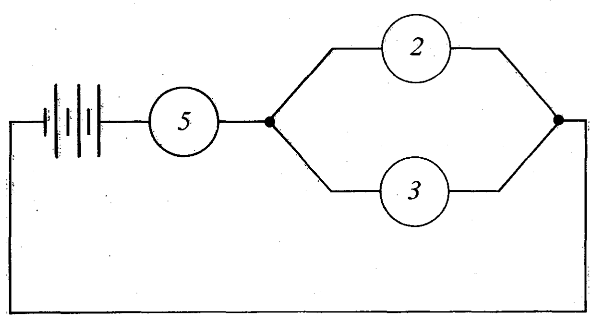
Or, 'If a lamp takes 2 amps, 2 coulombs pass through it every second'—a slightly less truthful statement.

Then, whenever we give pupils data that include a current in amps (or when they measure a current) we ask them to interpret it thus:

The current is 2 amps; *that means*
2 coulombs per second.

Give pupils simple problems that ask them to interpret currents like that. (For example: the current through a lamp is 2 amps. What does that mean, in other words? How much electricity (charge) flows through the lamp in 10 minutes?) This is one of the rare places in our kind of teaching where routine drill seems necessary and wise. Pupils had better build familiarity quickly.

Draw a circuit that carries 5 amps and branches at one place into a 2-amp branch and a 3-amp one in parallel. Pupils picture the coulombs drifting 5 a second past any point in the main circuit, then 2 a second in one branch and 3 a second in the other.



* The P.S.S.C. programme for teaching school physics in U.S.A. did that. Some teachers, and many pupils, considered that a good, realistic, modern scheme; but it led to uncomfortably large numbers. For example, unit potential difference is then 1 joule per unit charge (one electron charge) and that is 6×10^{18} volts.

We use the metre-kilogram-second scheme, which leads directly to the practical units, such as 1 joule/coulomb. As a result we need a Millikan-experiment film to fit our teaching.

DEMONSTRATION CIRCUITS

Simple electric circuit Now is a good time for demonstration* circuits: a simple circuit with several lamps and one or two ammeters in it; then a circuit with branches, with several ammeters at interesting places.

* In earlier years we urged teachers strongly to let pupils try out their own circuits, learning by mistakes and enjoying success; but those same experiments if needed now should be shown quickly, to save time and to avoid boredom.

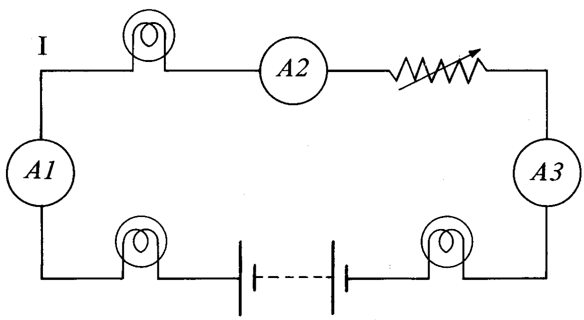
Demonstration 99 Series circuits and branching circuits

General knowledge of currents in series and branching circuits is an important part of pupils' familiarity with electricity.

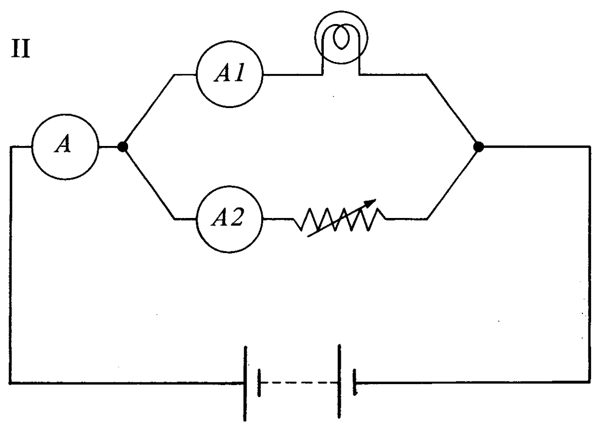
Examination questions may ask for such knowledge; but they are unlikely to stress numerical calculations of resistances in parallel.

At this stage, there should be quick demonstrations. The circuits should be mounted in the vertical plane so that the layout can be seen readily. In such demonstrations, where very clear display is needed, it is advisable to use straight, stiff, bare copper wire and to make connections with crocodile clips.

I



II



Apparatus

1 12-volt battery	item 176
6 d.c. ammeters (0–1 amp)	79
2 lamps (12-volt, 6-watt)	177
2 lampholders (S.B.C.) on bases	74
2 rheostats (10–15 ohms)	541/1

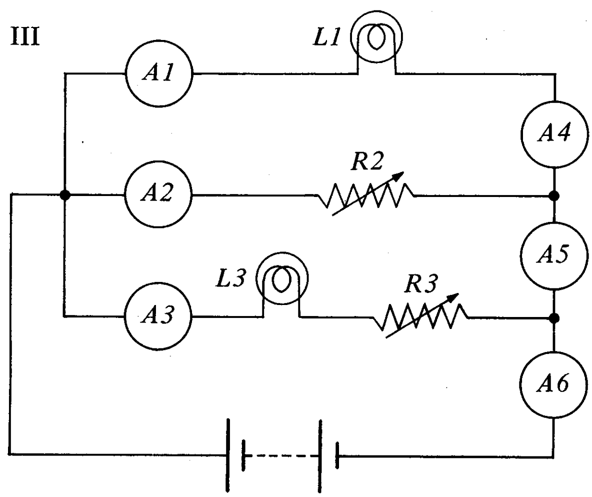
Procedure

a. Simple circuit Show a simple series circuit with several lamps and ammeters. (I)

b. Branching circuits Set up a circuit with branches. Insert ammeters at interesting places. The sketches give suggestions. (II)

Specimen readings for circuit III With a 12-volt battery and 12-volt 6-watt lamps, A_1 will read 0.5 amp. Adjust R_3 so that A_3 reads 0.3 amp and R_2 so that A_2 reads 0.2 amp. Then A_4 reads 0.5 amp, A_5 0.7 amp and A_6 1.0 amp.

III



Water circuit Also show a 'water circuit' again. That is best shown without branches or interchangeable 'resistances'. Its main purpose is to illustrate the general idea simply—not to build a complicated analogue. In commenting on a water circuit, liken a coulomb to a litre of water so a flow of a litre per minute corresponds to a flow of a coulomb per second or 1 amp.

We should be very careful to avoid reversing the logic in using that analogy. The proper line of argument is this:

(i) We know from simple experiments that *something* is the same all round the circuit, because lamps light equally all round and an ammeter moved from one place to another in the same circuit gives the same reading. We call that something which is the same all round the 'current' because that experimental property reminds us of a similar property for water in pipes.

(ii) With the water analogy in our mind, we think of the wires of the circuit as full of something that can be made to move once a battery is applied—rather like starting everyone seated round a tea table on a continuous rotation. We call that something, which we suppose fills the wires and is ready to move, 'electricity', or 'electric charge'—and we measure that in coulombs.

Add a pressure gauge and use it *to illustrate the idea of potential difference*—the main benefit of the model.

Model water circuit
Description of Apparatus

See *Teachers' Guide 3*

NOTE In earlier models, there was a suggestion of a *pair* of high-resistance tubes in *parallel*. That is confusing and should be avoided completely.

Demonstration 100a, b Water circuit

Apparatus

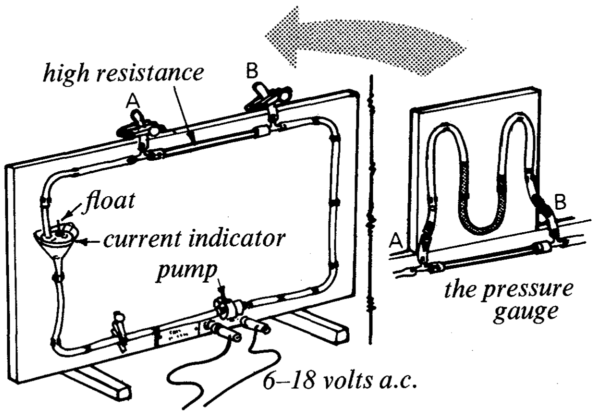
1 water circuit board	item 89
1 L.T. variable voltage supply	59

Preparation

Set up the board vertically. Connect the electric motor (which is incorporated in the pump) to the a.c. terminals of the L.T. variable voltage supply (*not* d.c.). The motor can take up to 16 volts. Fill the tubes with water by pouring it in at the funnel. A little fluorescein or a few drops of methyl orange can be added to make the water more visible.

The pump drives water round the circuit, the pump's pressure (e.m.f.) being dependent on the voltage applied to the pump's motor.

Put some coloured water in the pressure gauge; but leave some air above that water in each leg.



Procedure

First run the model without a pressure gauge. Then show how the pressure gauge must be connected. Point out that it measures *differences* of pressure.

Demonstrate the change of water-current with pressure, by changing the supply to the pump motor.

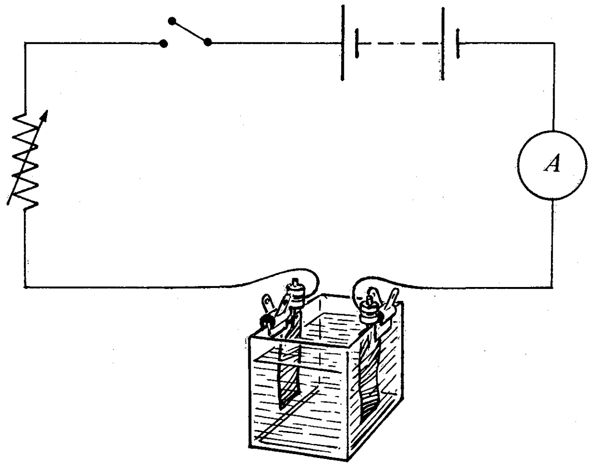
ELECTROLYSIS EXPERIMENTS

Unless there is a lot of spare time, these should be demonstrations.

Coulombs of charge taught by electrolysis To some pupils the feeling for coulombs comes most easily from electrolysis. If pupils have studied electrolysis in Chemistry and remember it, we may be able to use that knowledge. Chemistry will have provided background knowledge which makes the experiments quick to do and easy to interpret. In schools which are following the Nuffield Chemistry programme, we can omit the experiments below from our Physics course. Otherwise pupils should see simple electrolysis now.

Demonstration 101 Electrolysis of copper sulphate solution

This may be omitted if it has been done in Chemistry.



Apparatus

3 copper voltameters (exactly similar)‡	153
3 d.c. ammeters (0–1 amp)	79
3 rheostats (10–15 ohms)	541/1
3 12-volt batteries	176
chemical balance, preferably a direct reading one	
clock	
copper sulphate solution‡‡	

‡ The copper voltameter should be designed to make it easy to remove and replace the cathode. A typical voltameter consists of two clean copper electrodes held to the sides of a rectangular glass jar by bulldog clips and fitted with soldered terminals. This arrangement facilitates easy replacement in the same place.

‡‡ The electrolyte is a saturated solution of copper sulphate with 5% sulphuric acid.

Preparation

Before the lesson, set up three exactly similar circuits, each like the sketch. Adjust the rheostats to give suitable currents.

For typical electrodes having immersed area 8 cm × 5 cm, suitable currents are 1 A in one circuit and 0.5 A in each of the other two.

These correspond to current densities about 0.025 A per cm^2 and 0.012 A per cm^2, which should give stable deposits of copper.

Prepare the plates by a preliminary trial in which the rheostats can be adjusted. Then switch off and remove the cathode plates. Wash the plates and dry them. (To make sure that the plates are equally dry in the initial and final weighings, it is best to give them a final wash in alcohol; then burn the alcohol off and let the plates cool.)

Procedure

Remind pupils that like all metal ions, the blue copper ions carry positive charges. So the plate on which copper is to be collected must be connected to the *negative* of the battery.

Weigh the clean dry cathodes and replace them in the circuits.

Then switch on all three circuits. Quickly adjust the currents, if necessary, to 1 A, 0.5 A, 0.5 A.

After 10 minutes switch off the circuit carrying 1 A and one of the circuits carrying 0.5 A.

After 20 minutes switch off the third circuit. Remove the cathodes; wash them, dry them and weigh them, taking care to note which is which.

Pupils consider the weighings to see whether the mass of copper carried across is proportional to CURRENT × TIME.

Electrolysis of water If there is time to spare do a similar experiment with the electrolysis of water, and calculate the mass of hydrogen liberated by a known current for a known time and compare that with the mass of copper.

(Such a measurement will be essential in Year 5, so that pupils see and understand the measurement of e/M for hydrogen ions, which they compare with e/m for electrons. Therefore electrolysis of water may be postponed.)

Demonstration 102 Electrolysis of water *(OPTIONAL NOW)*

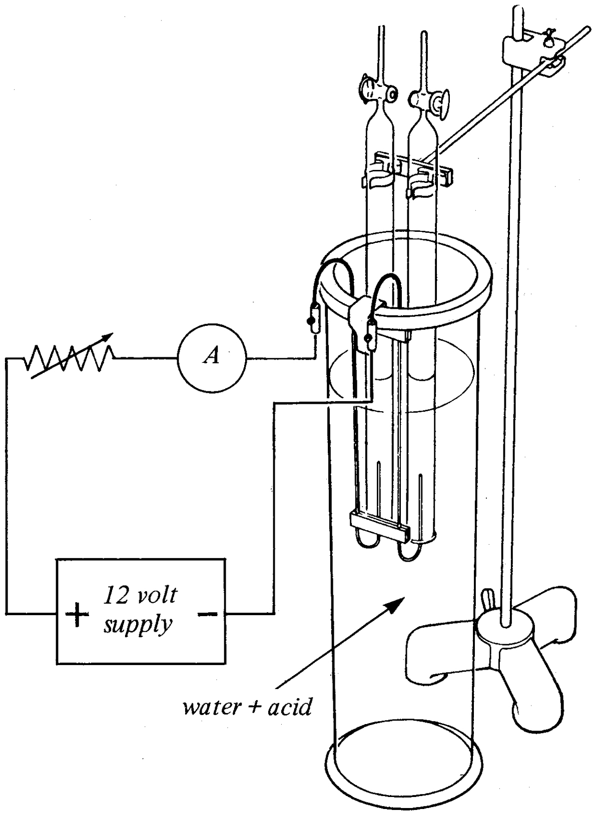
This should be omitted now if it has been shown in Chemistry.

Apparatus

1 Worcester gas voltameter kit	item 54
1 rheostat (10–15 ohms)	541/1
1 d.c. ammeter (0–1 amp)	79
1 12-volt battery	176
clock	
acidulated water (about 2% H_2SO_4)	

The L.T. variable voltage supply (item 59) can be used instead of the 12-volt battery and rheostat.

The 250-cm^3 burettes are very long. If a sufficiently tall jar is available, so that a burette can be pushed down into the jar until it is totally immersed, it can be filled simply by opening the tap. But, since that requires an unnecessarily tall jar the kit includes a device for filling a burette: a plastic bottle that can be squeezed.



Procedure

Connect the circuit as shown.

Only one of the two 250-cm^3 burettes is needed. Fill it with acidulated water after it is placed over the cathode. The filling is done as follows:

(i) Fill the large jar with electrolyte.

(ii) Use the plastic bottle as a syringe. Squeeze it firmly to expel some air, then connect it by a tube to the top of the burette. Open the burette's tap and release the bottle so that it sucks electrolyte up into the burette. Close the tap. Remove the bottle.

(iii) Repeat *(ii)* until the burette is full. Switch on the current and adjust it to 1 amp. (*Warning:* the position of the burette relative to the electrode has a marked effect upon the current.)

After that adjustment, switch off the current. Bring the water up to the top of the burette again.

Then let the current flow for a measured time, say 20 minutes.

Switch off, and read the volume of the hydrogen.

Taking the density of hydrogen as 8×10^{-4} gram/cm^3, calculate the mass of hydrogen liberated. From that, calculate CHARGE/MASS, e/M for hydrogen ions.

Note: It is unnecessary to adjust water levels before reading the volume of hydrogen, to correct for the pressure of the head of water. That would make a difference of a few per cent at most and would add an unscientific complication because this is clearly a fairly rough measurement.

Chemistry will certainly have provided a clear knowledge of the relative masses of hydrogen and copper ions. Copper experiments suggest that *if* the copper carried across consists of tiny atoms, all alike, then *probably* the electric current is moving across in tiny atoms of positive charge,* all alike—'an electric charge as rider on every copper horse'. The comparison with hydrogen suggests that only half as many copper atoms have to arrive for the same amount of CURRENT × TIME.

In modern chemistry teaching, we are likely to find valency given much less attention, so we should avoid mentioning chemical equivalents and keep to whole atoms. We emerge with the suggestion of a double charge for copper ions.

Even this demonstration will not be so convincing to pupils brought up on 'amps' and 'currents' as to those of a much earlier generation brought up on electrostatic charges, which led into the idea of moving charges in a circuit, and thus to current. However, the latter method had serious disadvantages of making electrical studies in school seem remote from the ordinary electric currents that ring bells or make motors work. As it is, we have to say again and again that [CURRENT × TIME] tells us how much electricity, how much CHARGE, has passed by. And again and again we illustrate that by comparison with water flow.

[WATER FLOW, in litres per min] × [time in mins]

tells us how many litres have flowed out of the tap. (The water circuit might be shown again here.)

ELECTROSTATIC CHARGES AND CURRENT CHARGES

Teachers who are skilful in an approach to electrostatics will be tempted to link up these charges in currents with the electrostatic charges that repel each other with the inverse-square law. True, they are charges of the same kind of electricity, but the phenomena seem so different, to beginners, that the linking of them is not very helpful. Above all, the moving charges in the wires of an electric circuit are moving through a lattice of opposite charges, so no electrostatic forces of attraction or repulsion are noticeable.* Pupils can be persuaded to pay lip-service to the identity of the two kinds of charge, but that does not seem to help their understanding of coulombs travelling round in electric circuits.

{**Rowland's experiment** We cannot repeat as a demonstration the famous experiment by Rowland. He managed to spin an insulating disc with charges on its rim and detect the tiny magnetic field near the centre of the disc due to the moving charges acting as a current. One can satisfy oneself by a rough calculation of the magnitudes involved that there is no chance of obtaining a big enough magnetic field for an ordinary demonstration.}

{In some recent discussions of physics teaching, Rowland's experiment has regained considerable importance, because it has become clear that, without it, we are likely to teach some things about charges in electrostatics and other things about moving charges in electric circuits and just assert that these two kinds of charge are the same thing, without showing any basis for that assertion. There is that risk—but there are similar risks in our teaching of Newton's Laws and many other things. It would be a great pity to divert time and energy into trying to perform a Rowland experiment. Nearly all the demonstrations that look successful are really showing quite other effects. For example, a compass needle held near the moving belt of a Van de Graaff machine will often be deflected when the belt is running; but investigation shows that the deflections, which are arbitrary and variable, are due to electrostatic inductive effects: the result of uneven charges on the belt inducing charges on the compass needle.}

Charging a capacitor However, we can pile up electric charges at rest on the plates of a capacitor, drawing them equally well from a

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*The facts of electrolysis make ions plausible but not necessary. The facts of chemistry known in the nineteenth century made molecules and atoms plausible, but not necessary.

By the beginning of this century all scientists felt forced to believe in atoms; and then it was easy to accept the view that all atoms of a given element must be identical.

It came as an uncanny surprise when experiments showed the existence of isotopes with different masses for the same element. That might make us more cautious about assuming that all ions have the same charge (or multiples of the same basic charge). However, we are assured by Millikan's experiment that not only does electricity come in small atoms of charge, but those atoms are all the same size.

* Since there is a potential difference between the ends of any ordinary wire when a current is flowing, there must be an electric field along it and a tiny distribution of net charges which will exert minute forces—far too small to be considered here.

battery or from an electrostatic device, and then show that those charges have both 'electrostatic' properties and 'electric current making' properties. Then, we can suggest that the electric charge that we measure by (CURRENT) × (TIME) is the same kind of thing as the electric charge that we gather by rubbing plastic with wool or pile up with the help of a Van de Graaff machine.

Use a large capacitor. Explain to pupils that it is a pair of metal plates separated by an insulator—a sandwich rolled up and housed in a box. Use *two* galvanometers to show charges running *to* one plate, and *from* the other.

These currents last only a very short time and then there is no more current (yet, as pupils will see, there are charges on the capacitor, which can run out of it again).

Here pupils see the 'electric current' type of coulombs running from a current source to the plates of the capacitor. The charges may be resting there.

Then, show charges accumulated on a capacitor's plates producing sparks or making an electroscope leaf rise. Unfortunately the charges stored on the capacitor plates by an ordinary low voltage battery will not make sparks or affect an electroscope noticeably. Therefore, we have to extend this first experiment to higher and higher charging voltages.

Thus pupils should see that charges come from two kinds of source:

CURRENT SOURCES: batteries, power-packs* (which we state are equivalent to batteries), dynamos.

ELECTROSTATIC SOURCES: a piece of plastic rubbed with wool, an electrophorus, a Van de Graaff machine**

And in each case, when charges have been obtained pupils should see them showing both kinds of behaviour:

ELECTRIC CURRENT BEHAVIOUR: moving the pointer of a sensitive moving-coil meter, lighting a lamp; and possibly chemical effects, detected by feeling a shock.

ELECTROSTATIC BEHAVIOUR: making sparks; attracting small pieces of metal leaf; deflecting an electroscope.

We suggest teaching should include a small selection of the experiments below.

Demonstration 103 Experiments with capacitors

Apparatus

2 demonstration meters‡	item 70
2 d.c. dials (2.5–0–2.5 mA)	71/4
1 EHT power supply	14
1 HT power supply	15
1 Van de Graaff generator‡‡	60/1
1 12-volt battery	176
1 lampholder (B.C.) on base	162
1 240-volt 15-watt lamp	
1 switch	224
1 500 μF electrolytic capacitor (50 V working)	132C
1 50 μF electrolytic capacitor (350 V working)	132D
1 0.001 μF capacitor (20 kV working)	132E
1 4.7 kΩ resistor (2 watt)	132J
1 100 kΩ resistor (2 watt)	132L

‡ The demonstration meters should be identical.
‡‡ A Wimshurst could be used as a less satisfactory substitute.

Preparation

Before the electrolytic capacitors are used connect them directly across the battery for about a minute to ensure that the plates are formed. Make the connections with correct polarity.

Procedure

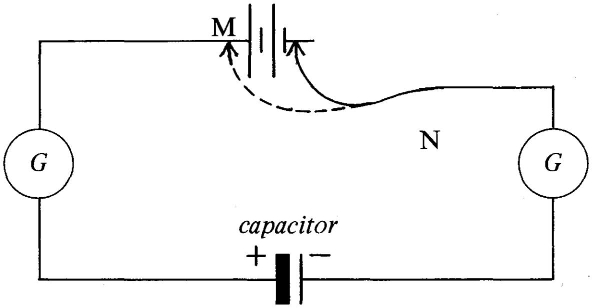
a. *Charging a 500 μF electrolytic capacitor (50-volt working)*

Set up the circuit shown with 4 volts from the battery and the 500 μF electrolytic capacitor.

When the switch is closed, the two galvanometers show brief charging currents. Repeat this several times while pupils watch the unexpected pulses. Then let the capacitor discharge by

* Whenever the high voltage power-pack is used, show that it is not a disguised electrostatic device, but can perfectly well drive a steady current through a high resistance, just like a large battery. Run a wire from one terminal to a high resistance, on through a microammeter, to the other terminal. The microammeter shows a deflection; and it shows a similar deflection when it is connected to an ordinary 6-volt battery through a lower resistance (for example, one's own body).

** If Wimshurst is used instead of the Van de Graaff machine, be careful not to produce spurious effects by sudden pulses of charge. Connect the output from the Wimshurst to one plate of a big air-capacitor, with the other plate *earthed*, to act as a smoothing device.



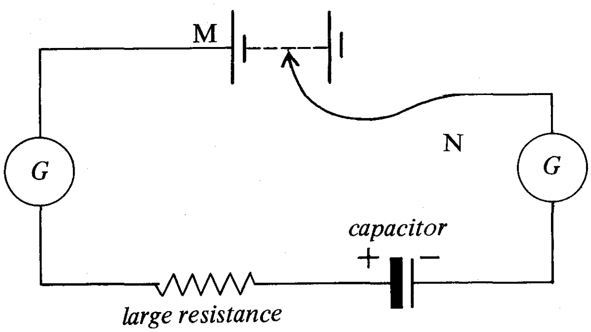
disconnecting the lead N from the battery and connecting it to M.

b. *Charging a 500 μF capacitor through a large resistance*

Modify the circuit above by including a 4.7 kΩ resistor in series with the capacitor.

Charge the capacitor as before, but use 9 to 12 volts from the battery to show the slow charging process. The current dies exponentially as the charge rises towards the full value.

Again connect lead N to lead M to show the discharge through the resistor.



c. *Charging a 0.001 μF capacitor to a high voltage and then short circuiting it*

Arrange the demonstration as follows:

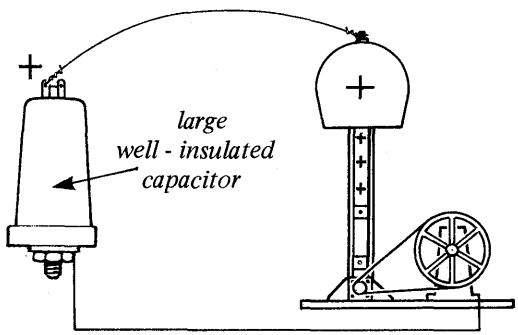
Set the E.H.T. power supply to provide 5 kV. Hold the capacitor very firmly in a clamp and connect the stud mounting end to the earthed negative terminal of the power supply. Connect the positive terminal to the capacitor through a 100 kΩ resistor. (If the power supply has a built-in 50 MΩ safety resistance, this could be used instead of the 100 kΩ resistor, but as it is less obviously part of the circuit an external 100 kΩ resistor is better.)

Connect the end of the resistor to the top of the capacitor with a well-insulated flexible lead held by hand. After a moment or two remove this lead. To show that the charges which are now resting on the plates can produce 'electrostatic effects', bring another well-insulated lead from one terminal of the capacitor round to the other terminal. Pupils see a small spark.* They may consider that a sign of electrostatic behaviour, though we may say there is a current in the spark. For a fully electrostatic effect, charge the capacitor again from the E.H.T.; then connect the capacitor's terminals to the leaf and case of an electroscope. (An ordinary electroscope gives appreciable deflections for voltages in the range a few hundred to a few thousand volts.)

Note : This needs some care The E.H.T. supply is limited to 3 milliamps; but the capacitor when fully charged by the E.H.T. to 5000 volts is ready to drive a very large *initial* discharge-current through a body resistance of several thousand ohms. However, the charge stored is only 5 microcoulombs, and the current would die to a trivial value in a few microseconds. Yet the shock would be a very unpleasant 'bite' for a person. All that is needed is careful use of a well-insulated flying lead.

d. *Repeat of* **c.** *using an electrostatic generator*

Repeat the last experiment using a Van de Graaff generator (or Wimshurst). Make sure the capacitor is firmly clamped.



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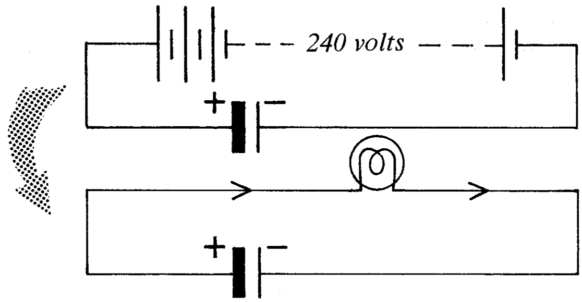
* Both the length of a spark and the energy dissipated impress people. The length of spark is roughly proportional to the voltage to which the capacitor is charged; and that is limited by the construction of the capacitor. The energy dissipated on discharge increases in proportion to the capacity *and* varies as the square of the voltage. The bigger the voltage, the much more impressive the spark. A limitation in voltage may be compensated by increase of capacity: arrange by placing several capacitors in parallel.

Where a Wimshurst is used, the connection can be made directly. With a Van de Graaff, a flying lead must be used. Hold the well-insulated flying lead by hand against the sphere, so that it can be removed easily and used to short-circuit the capacitor.

Notes

1. *This demonstration needs care* The initial current will be whatever the Van de Graaff's high voltage can drive. The Van de Graaff sphere alone has a small capacitance; so when one touches it the discharging current drops rapidly and only a fairly small 'bite' is felt. But the external capacitor stores about 100 times as much charge so its discharge-current will last longer and could hurt much more. Also the fat spark (a centimetre or more) can burn. All that is needed is careful use of a well-insulated flying lead.

2. The capacitor suggested is not designed for use with such high voltages, so it may break down internally. That is in no way dangerous, but makes it advisable to have one or two spares.



e. *50 μF capacitor discharged through a lamp*

Charge a 50 μF electrolytic capacitor (350 volt working) from the H.T. power supply set to give 240 volts. Include a safety resistor of 100 kΩ in the charging circuit. Allow ½ minute for charging.

Disconnect the supply and allow the capacitor to discharge through a 240 volt 15 watt mains lamp. (The safety resistor should *not* be included when discharging.)

Demonstration 104 Dancing men: Preparation for Millikan

This replaces the 'Macro-Millikan' model of the first edition.*

Apparatus

2 large metal plates	
I E.H.T. power supply	item 142
aluminium *leaf*	58A
scissors	
3 pillars of insulator	

Preparation

Place one metal plate on the table and connect it to earth. Hold the other plate about 10 cm above the earthed plate, horizontal and insulated.

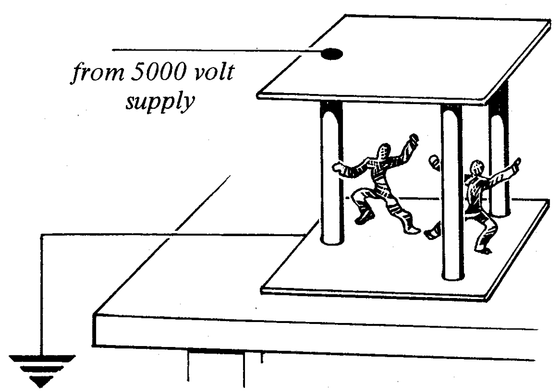
Cut or tear from the book some small scraps (1 cm) of metal leaf. (Or cut them in the shape of small men, say 2½ cm high.)

Procedure

Connect the two plates to the E.H.T. supply to establish a vertical electric field in the space between them. Place the scraps of leaf in the space between the plates. Then the scraps acquire charges when they touch either plate and are driven to the other plate; so they dance up and down in the space between the plates.

To show that the electrostatic charges will maintain a similar dance, replace the upper plate by a sheet of plastic. Charge the plastic by rubbing.

(This also works well on a small scale with a shallow plastic cheese box, charged by scratching it with a finger nail—a good home experiment.)



* That was a giant model, intended to show the general idea of Millikan's experiment. However it was expensive to make, not easy to run; and it was apt, under pressures in the later part of this Year, to *replace* the Millikan experiment itself so that pupils did not see the real experiment or its film! Pupils were thereby at a sad disadvantage in experience and in preparation for a possible examination question. The rough demonstration suggested now is quick and helpful; it is less likely to give the feeling that it can replace the actual experiment.

Show two lamps, a low voltage lamp and a high voltage lamp that take the same current but obviously give quite different amounts of light. The most striking form is to put the two lamps in series on the mains. That shows clearly that the ammeter reading (the current in coulombs/second) is not enough by itself to tell us how much light or heat to expect.

Demonstration 105 Comparing lamps

AIM To show quickly that two lamps which take about the same current may give quite different amounts of light: thus to lead to the need for VOLTAGE as well as CURRENT in the specification.

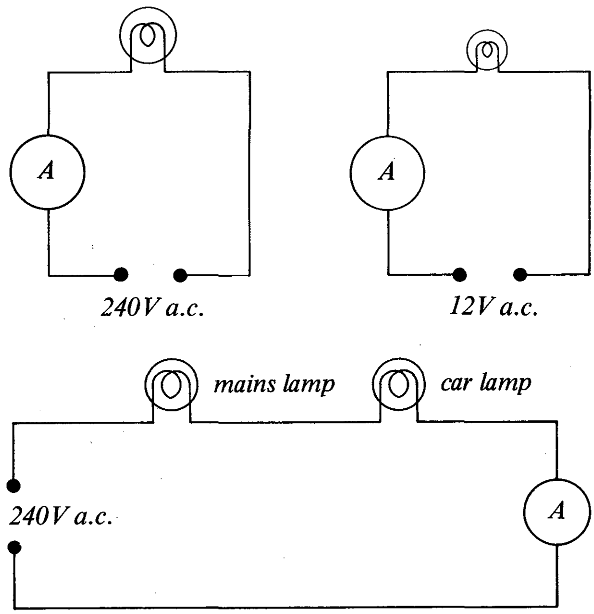
Apparatus

1 lamp holder (B.C.) on base‡	item 162
1 lamp holder (S.B.C.) on base	74
1 240-volt 100-watt B.C. lamp	558
1 lamp (12 volt, 6 watt)	177
1 demonstration meter	70
1 a.c. dial: 1 amp	71/8
1 transformer	27

‡The two lamp holders *must* each be fitted with insulated terminals.

Procedure

a. Set up separate circuits in which a mains lamp taking about 0.4 amp and car side-light lamp taking about 0.5 amp are connected to a 240-volt supply and a 12-volt supply respectively.



b. Connect the two lamp bases in series with the ammeter and the 240-volt supply.

Energy from electric supplies Any energy that we receive from an electric supply, whatever its form (radiation, or heat, etc.), can now be measured in joules. As long as a dynamo or battery maintains an electric current through a lamp or motor, we continue to obtain a stream of energy in some other form. And we can measure the energy produced in that other form, by catching radiation in ink, or by giving heat to water, or by measuring the mechanical energy delivered by a motor, etc. So we can find out how many joules are being delivered, per second, *FROM* electrical form *TO* some other form.

Experiments show that the rate at which we obtain the output energy in (joules/second) goes in direct proportion to the rate at which coulombs are passing in (coulombs/second), which the ammeter tells us.

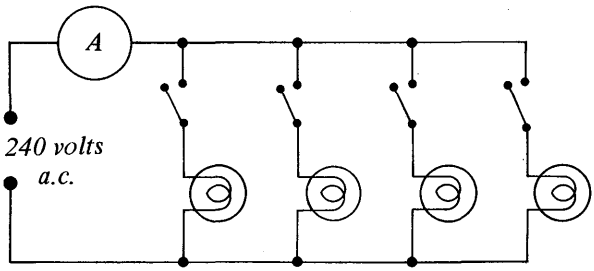
We can demonstrate that by having one, then two, then three, etc., lamps in parallel all fully lit. An ammeter shows that the currents run in proportions 1:2:3:... Common sense tells us that the rate of radiation goes up in the same proportions.

Demonstration 106 Lamps in parallel

Apparatus

4 240-volt, 60-watt lamps	
4 lamp holders (B.C.) on base	item 162
4 single-pole switches	
1 demonstration meter	70
1 a.c. dial: 1 amp	71/8

The lamp holder bases and switches should be fitted with insulated terminals.



Procedure

Connect the ammeter and the four lamp holders with switches to the mains supply, as in the diagram.

Show the current as first one, then two, then more lamps are switched on.

Instead of discussing how fast energy comes out, we might ask how much energy comes out in a measured time, one second or one minute. Then we see that the total output energy is directly proportional to CURRENT × TIME, or CHARGE, or the 'number of coulombs' of electricity that pass—measured by ammeter and clock. But CHARGE cannot be the only factor: pupils have seen a low voltage lamp and a high voltage lamp take the same current but give out quite different amounts of light. We also need a device that tells us how many joules of energy are delivered *by each coulomb* going through the lamp or motor. That is the device we call a voltmeter.

Just as a mass of one kilogram can transfer more energy if the cliff it falls off is 100 metres high than if it is only 10 metres high, so a coulomb of electricity delivers more energy if it flows between two points having a p.d. of 100 volts than if it falls through only 10 volts.

For fast pupils, some discussion like that above will serve to introduce voltmeters. For slower pupils it is probably better to take a crude operational viewpoint and just show how to connect a voltmeter across a lamp or motor. Then assert that the voltmeter is a device for counting how many joules each coulomb delivers as it travels through the lamp or motor.

{Teaching by assertion is a weak method; and if we indulge in it much we shall give science a poor name. Yet occasionally we may save pupils from confusing arguments for which they are not yet ready; and then we may be wise to make assertions. These are not so damaging if we ourselves remember clearly that we have made them.}

Voltmeters Ignorance (superstition?) concerning voltage has given Electricity a poor image for pupils in school physics, particularly among girls. The fault is chiefly ours, if our teaching is too didactic—with too much assertion, too much taken for granted, and too few simple introductory experiments.

We hope that our Nuffield programme has led pupils into enjoying Electricity with the Worcester circuit kit and the Westminster electromagnetic kit; but even now a few may not be ready to plunge into *potential difference* unafraid. We should offer them the two introductory approaches that were suggested in earlier Years:

(i) an experiment that shows a voltmeter as a 'cell counter'.

(ii) direct instruction—without explanation, on this rare occasion—saying 'this is how to use a voltmeter' and 'here is what we do with the number the voltmeter tells us'.

We trust that by the end of this Year, pupils will know very well how to connect a voltmeter 'across' the item being investigated; and how to use its reading in calculating power. That familiarity may have to take precedence over understanding that potential difference is a measure of energy-transfer per coulomb; and it should certainly take precedence over formal experiments to 'prove' Ohm's Law.

Analogy for Voltmeter It may be helpful to liken the current flow of coulombs to a flow of cars along a main road. We suppose that every driver arrives at a point A on the road with the same amount of money in his pocket and has spent all of it by the time he reaches a point B.

To find out how much money that is, we do not hold up every car and examine the drivers' finances, but instead arrange to divert just a few cars out on a side road at A, along a small lane and back to the main road at B. Somewhere on the lane there is a hold-up gang who empty the pockets of each driver in the small diverted stream. This is, of course, a model of the *working* voltmeter which is really a milliammeter in disguise.

The more rational analogue, a pressure gauge attached to a water circuit, raises quite a difficult detailed picture for pupils to understand if they think of a gauge with (apparently) only one inlet. They should see the model water circuit with a pressure gauge that has *two* connections to the flow-line—e.g. a U-tube of ink. We suggested a water-circuit demonstration earlier because we wanted to prepare for this very useful demonstration. It is better to show the earlier demonstration without a pressure gauge in earlier teaching, and to install one now, pointing out that it corresponds to a voltmeter.

Whatever explanation we give, we end up by saying that a voltmeter measures the energy transferred *FROM* electrical form *TO* heat or mechanical form, by each coulomb passing through part of the circuit across which the voltmeter is connected. Then pupils do several experiments.

† Class Expt 107 The voltmeter as a cell counter

(This could be done as a demonstration to save time, but the lasting value would be much smaller for pupils who consider voltmeters mysterious. Each pupil needs to get his hands on one.)

Apparatus

From Worcester Circuit Board kit	item 52
for *each pair*:	
3 U2 cells	52B
3 lamps	52A
3 spring connectors with lampholders	52D
spring connectors	52E
2 plug/croc lead	52I
2 croc/croc leads	52J
16 Worcester Circuit Boards‡	52C
16 d.c. voltmeters, 0 to 5 volts	80
16 d.c. ammeters, 0 to 1 amp	79

‡ It is not necessary to use the circuit boards. Schools which do not follow Nuffield Year 2 and have no circuit boards should not buy them for this. Any arrangement that enables pupils to connect up cells and voltmeter will suffice, though the circuit board is clear and convenient and saves time.

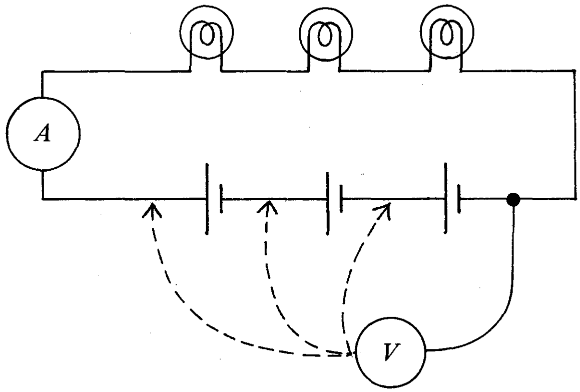
Procedure

Pupils follow these instructions:

* * * * *

Set up a circuit with three cells and three lamps all in series, as in the diagram.

Attach two long, flexible wires ('leads') to the voltmeter.



Switch on the lamps, and keep them running.

Connect the voltmeter leads to one cell, then across two cells, then across three. Record the reading of the voltmeter each time.

How many cells are needed to light one lamp fully?

How many cells to light two lamps fully? Three lamps fully?

What does the voltmeter tell you? What does it count?

Is the voltmeter connected in series with the lamps or in parallel?

What does an ammeter count?

* * * * *

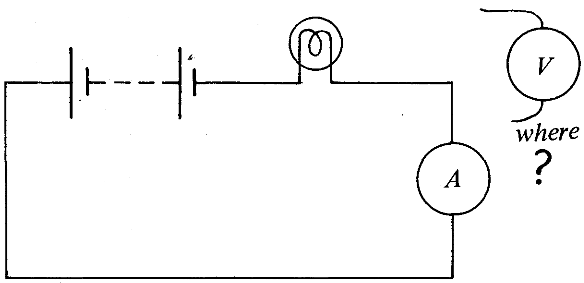
Class Expt 108 Using a voltmeter

Apparatus

4 (or more) 12-volt batteries	item 176
16 lamps (12-volt 6-watt)	177
16 lamp holders (S.B.C.) on bases	74
16 d.c. ammeters (0–1 amp)	79
16 d.c. voltmeters (0–15 volt)	179
16 switches	237

Preparation

Arrange the 12-volt batteries so that several groups of pupils can operate from each battery.



Procedure

Pupils follow these instructions.

* * * * *

Connect up a simple circuit of battery, lamp in its holder, ammeter and switch.

Switch on, to see the lamp light up. Note the current.

Where would you add a voltmeter to see the voltage for the lamp?

Carry out your suggestion: add a voltmeter. What happens? Discuss with your teacher.

* * * * *

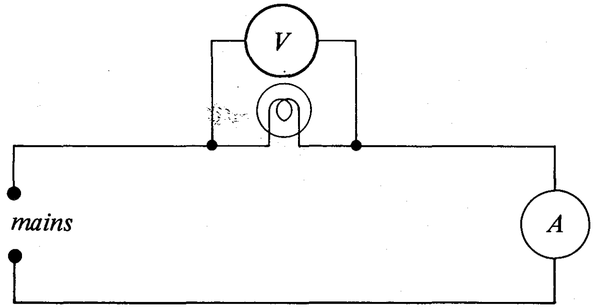
At this early stage, pupils may learn more by making a mistake—placing the voltmeter in series. Voltmeters look too much like ammeters; and anyway, pupils have been connecting most things in series so far. Then, for some, tell the pressure-gauge story; for others, just assert the rule or custom for placing voltmeters.

Demonstration 109 Connecting a voltmeter

This experiment is a supplement to the previous class experiment 108, this time with the a.c. mains.

Apparatus

1 240-volt, 60-watt lamp	item 559
1 lamp holder (B.C.) on base	162
2 demonstration meters	70
1 a.c. dial: 1 amp	71/8
1 a.c. dial: 300 volt	71/9

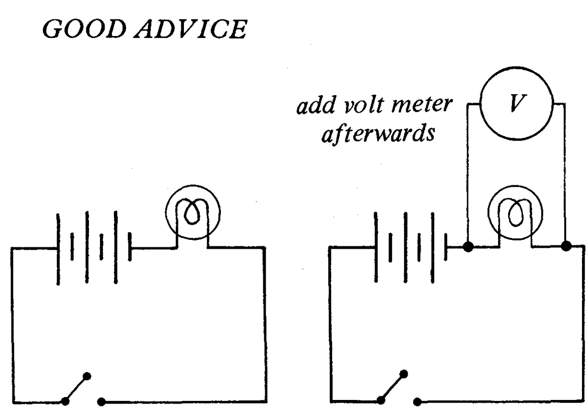


Procedure

(i) Set up the circuit, with mains supply.
(ii) Switch off and connect the voltmeter across the lamp. Switch on.

In discussing such experiments, we say:

'240 volts means 240 joules per coulomb: *volt* is just shorthand for *joules/coulomb* which is itself an abbreviated form of *joules of energy transferred from electrical form to another form in that lamp, for every coulomb passing through it.*'



Demonstration 109X Connecting a voltmeter *(OPTIONAL EXTRA to help a slow group)*

Apparatus

2 240-volt, 60-watt lamps	item 559
2 lamp holders (B.C.) on bases	162
2 demonstration meters	70
1 a.c. dial: 0–300 volt	71/9
1 a.c. dial: 0–1 amp	71/8
1 radiant heater	58C

Procedure

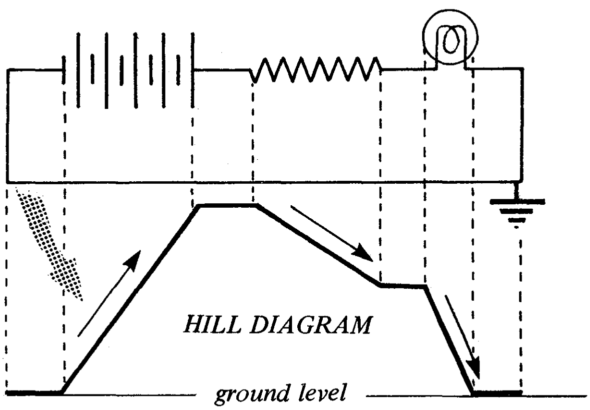
a. Set up a simple series circuit of mains lamp and ammeter. Show how to connect the voltmeter in across the lamp.

b. Insert an electric heating element in the circuit. Show how the voltmeter may be connected across, first, the lamp, and then, the heating element.

c. Connect up a circuit of two similar lamps in series and repeat.

Note: Remind pupils that the circuit should always be switched off while changes in wiring are made.

Hill diagrams Talking about voltmeters and the voltage that they measure, we often speak of a coulomb 'falling through' a certain p.d. We might sketch diagrams of hilly terrain. The coulomb is boosted up through the battery; it runs downhill round the circuit, delivering its stock of energy.



Overall test of voltmeter's action Young pupils will not gain much insight into the working of a voltmeter if they are carried through a detailed investigation of its action, or a calibration to prove that it measures what we claim. But they should try a short test. They should see a voltmeter applied to successive batteries: one cell, two cells, three cells ... in series.

{This is an overall ('thermodynamic') test. If the voltmeter is a proper device to show energy transferred per coulomb (and if the imaginary coulomb passing through a battery gains in electrical energy at the expense of chemical energy) we should expect three cells in series to give each coulomb three times as much electrical energy as a single cell. And we should expect to find the voltmeter across three batteries reading three times as much as across one. In that expectation we are trusting that the conservation of energy extends to electrical energy—and Joule investigated that as well as heat.}

This test with batteries only tests a *necessary* condition. It does not prove that voltmeters measure energy-transfer per coulomb; but a failure of this overall test would disprove our contention*. It supports the preliminary description of a voltmeter as a 'cell counter'.

(Note that this treatment of voltmeters does *not* involve us in any logical difficulty or threat of dishonesty if we use such a voltmeter later on to investigate the Ohm's-Law behaviour of a metal wire. We have not opened up the voltmeter; we have not worked out the resistance necessary to convert its internal milliammeter into a voltmeter; so we have not assumed what we want to prove; instead we offer *external* tests. See the Note on Logic and Voltmeters in Chapter 12.)

* The position here is rather like that of an experimental test of a theory. An experiment cannot prove that a theory is right; but it may prove a theory is wrong.

Class Expt 110 Does your voltmeter measure what it is supposed to? A test

Apparatus

4 (or more) 12-volt batteries‡ item 176
16 voltmeters (0–15 volt) 179

‡ The 12-volt batteries must be such that it is possible to tap off intermediate voltages. 4-mm sockets may help; but the battery's acid may contaminate sockets and plugs. Large alligator clips already attached to wires would be better teaching for this messy use.

Ordinary car batteries can be used, but in some modern types it is not easy to take off intermediate voltages. Some manufacturers supply batteries adapted for school use, and we recommend these.

A group of 1.5-volt cells would suffice here instead, but that would not provide the large steady currents needed in later experiments.

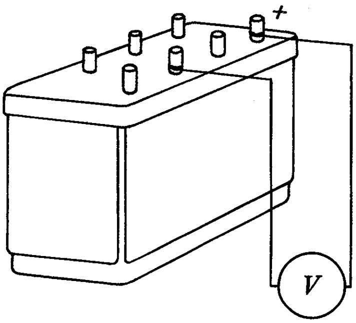
Procedure

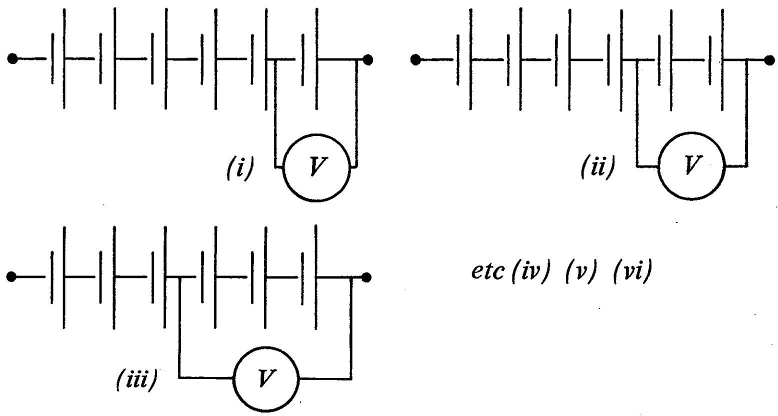
Pupils follow these instructions.

* * * * *

Apply your voltmeter to just one of the cells of the 12-volt battery. Then to two cells. Then three, four, five and six cells. Does your voltmeter pass this test?

* * * * *





Calibration of voltmeter *(ADVANCED BUFFER OPTION)* Pupils could, of course, proceed to test one point on a voltmeter's scale by an absolute measurement. They could send a current through a coil of wire immersed in water, measure the current, measure the time, and measure the heat developed in water. Then, if they kept a voltmeter connected across the coil during the experiment, they could compare its reading with the measured energy transfer (from electrical to heat) for every coulomb passing through the coil. That would compare a reading in volts with a measurement in *thermal units/coulomb*, which they then convert into *joules/coulomb*.

For that conversion, pupils would rely on our assurance that heat is a form of energy equivalent to mechanical energy; and they need to know a conversion rate between *thermal units* and *joules*.

And, for honest logic, they would have to make sure that the conversion factor, 4200, was not drawn from *electrical* experiments in the later work of Joule and others—because that might lead to arguing in a circle. However, there are plenty of good mechanical measurements of 'J', and we can rely upon them.

That experiment will test whether the voltmeter *does* measure joules/coulomb at some chosen point on its scale. It may be very important in a logical development of physics, but it is a difficult, rather messy experiment that pupils are likely to find dull.

Teachers who are skilful in running this as a class experiment, avoiding too many detailed instructions, but maintaining an enthusiastic sense of the voltmeter being on trial, might try this with a fast group. Others, who consider that the difficulties of thermal measurements make this a confusing test, may prefer to leave it out but keep it in mind for those pupils who ask about it. This is a place where we should ask most pupils to take our word for the instrument's action—as we do with stopwatches, balances and (quite often) ammeters.

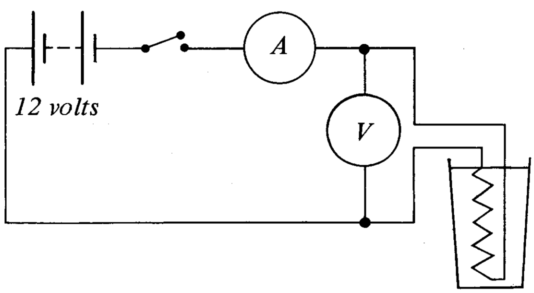
Class Expt 110X Calibrating a voltmeter *(ADVANCED BUFFER OPTION)*

Apparatus

Apparatus needed by *each pair*. (We think it very unlikely that pupils will—or should—try this test. So while we give it here, as an assurance for teachers about logic, we omit it in *Pupils' Text*.)

1 immersion heater	item 75
1 voltmeter (0–15 volt)	179
1 ammeter (0–5 amp)	178
1 thermometer	542
1 stopwatch or stopclock	507
1 plastic cup‡	164
1 (or more) 12-volt batteries	176

‡ Plastic drinking-cups are suitable for this experiment having a low heat capacity, or perspex containers or even transparent sandwich bags could be used.



Procedure

Pupils follow these instructions.

* * * * *

Place about 200 grams of cold water in a container. Weigh it. Then place the immersion heater in the water and connect it into the circuit shown. Record the temperature.

Switch the circuit on and start the watch at the same instant. Allow the current to flow for two minutes, *using the heater as a stirrer*. Record the ammeter and voltmeter readings.

After two minutes, switch off the current. Stir the water again and note the maximum temperature, even if you have to wait several minutes, stirring constantly, until the temperature rises no more.

Then calculate the voltage from your measurements of the heating. Pretend that you did not have a voltmeter so you must use the heat measurements to calculate the voltage. To work out the voltage, calculate each of the following:

(i) The charge, measured in coulombs, that has passed through the heater.

(ii) The energy delivered, first in kg-of-water ·°C then in joules. (Remember the factor 4200.)

(iii) The energy-transfer for each coulomb. This is the p.d. measured in volts.

Now compare that result with the reading of your voltmeter. Remember* that *it is the voltmeter that is under test*; so you should pretend that your heat measurements are reliable.

(In all heat measurements there is considerable leakage—conduction, convection and radiation all carry heat away, so that you do not measure the total amount of heat accurately. There are methods of allowing for those losses, as you may see in descriptions of Joule's experiments; but they would make your work too long and difficult. So you should treat this as an 'experiment of principle' to see how a voltmeter could be calibrated.)

* * * * *

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* Two things encourage pupils to make an unfortunate reversal of logic:

(a) The meter itself looks so shiny and 'scientific' that pupils are willing to trust it as they already trust stop-watches and ammeters unquestioningly.

(b) If they have some feeling for the perils of calorimetry, they know their experiment cannot yield a very reliable result for the voltage which is to serve as the calculated standard. Yet we should keep the logic clear or pupils may acquire a mistaken view of scientific experimenting in general and electrical measurements in particular.

We believe the rare pupil who takes on this experiment because he is ahead of the others, or has special interests, will come to appreciate this matter of logic.

E.M.F

Pupils may be encouraged to think informally of potential difference as 'electrical pressure difference' between the ends of some part of a circuit where electrical energy is transferred into heat, etc., and of voltmeters as devices to measure that energy transfer, for each coulomb passing through that part.

Presently, pupils apply the voltmeter to the battery itself. Of course that is the same as applying the voltmeter to the whole of the outside circuit when there is one; but there may be no outside circuit and yet the voltmeter gives a reading.

Discuss that with pupils and suggest that the voltmeter connected across the battery tells, in one sense, the energy-transfer the other way round; the transfer per coulomb *FROM* electrical *TO* other forms all round the circuit. But in another sense it tells the energy-transfer *FROM* chemical form *TO* electrical form *in the battery*. We call that the e.m.f. of the battery. There it shows the uphill raising given to the coulomb which then slides downhill round the circuit.

Picture a 6-volt battery as a fuel agent giving 6 joules to every coulomb and instructing it 'Remember you must spend *all* this energy on your trip round the circuit.'

We may liken the battery to a lift or moving ramp—such as the machine used to raise coal or gravel to the top of a tower for sorting. Electric charge, measured in coulombs, is hauled or pushed by the battery up to the top; then as it travels round the rest of the circuit it is 'running downhill', changing the electrical energy it has gained from the battery into heat, etc., as it makes some kind of collisions in the wires. Then as each piece of electricity, each coulomb, reaches the battery again, it is raised up again with a new dose of energy, at the expense of chemical energy in the battery.

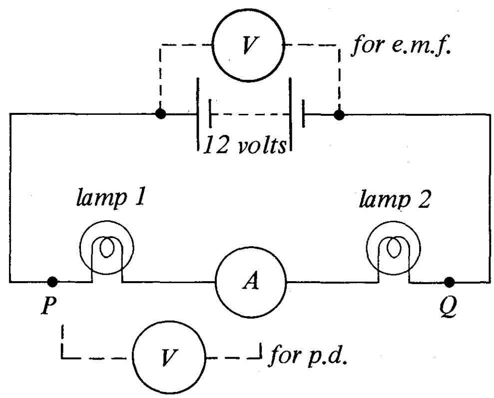
Demonstration 111 P.d. and e.m.f

Apparatus

1 12-volt battery	item 176
2 lamps (12-volt 6-watt)	177
2 lamp holders (S.B.C.) on bases	74
2 demonstration meters	70
1 d.c. dial: 1 amp	71/1
1 d.c. dial: 15 volt	71/10

Procedure

Connect battery, ammeter and lamps in series as shown. Arrange them in an actual pattern like that.



Support the voltmeter *below* the battery and connect it first across lamp 1, then across the ammeter, then across lamp 2, then across the three together (between P and Q). Note the p.d. in each case.

Then hold the voltmeter *above* the battery—a purely didactic move—and connect it across the battery. Ask for a new interpretation (e.m.f.).

With a very fast group it may be worth repeating this demonstration with a battery possessing internal resistance—e.g. an accumulator with a series resistance of Eureka wire, all concealed in a cardboard box.

OSCILLOSCOPES *(OPTIONAL NOW)*

Oscilloscope. Drawing wave-form of voltage We hope that oscilloscopes, both the large demonstration one and smaller ones for class experiments, will be given plenty of use in our programme.

At some stage, in Year 3 for a few, in Year 4 if there is time, but otherwise in Year 5, pupils should play with an oscilloscope and learn to use its controls capably. Until they have practised, many will need help in obtaining a suitable trace. But pupils should use their own oscilloscopes as early as they can be provided.

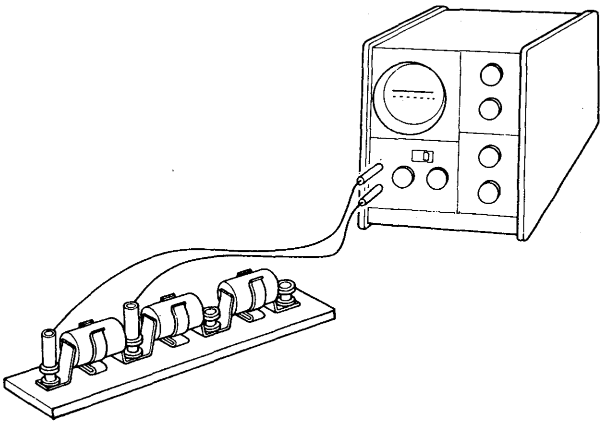
Here are some examples:

a. Oscilloscope as voltmeter A C.R.O. is a good voltmeter: the electron-stream obeys instructions to move up or down practically instantaneously and the 'input resistance' of the device is very high.

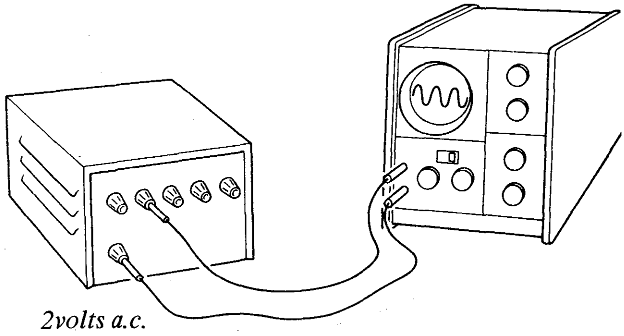
For alternating voltages, it is not necessary to sweep the trace across. The spot can be left to run up and down and the total height, twice the amplitude, measured. For d.c. voltages the spot should be kept sweeping across so that the screen is not damaged.

The C.R.O. acts as an uncalibrated voltmeter. We must either apply a known e.m.f. from a cell, treated as our 'standard cell', or compare the C.R.O. with an ordinary voltmeter.

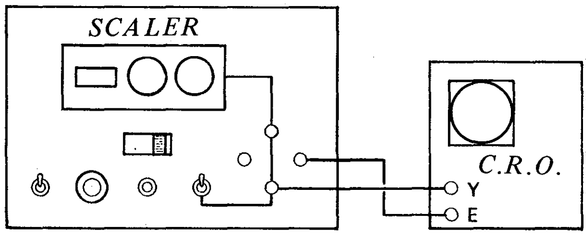
Now that oscilloscopes are in such common use in testing laboratories and research laboratories, this example of using a C.R.O. as a voltmeter is one that pupils should see and, if possible, come to regard as an ordinary use.



b. Show the wave-form of the mains a.c. Take a small sample from a transformer.

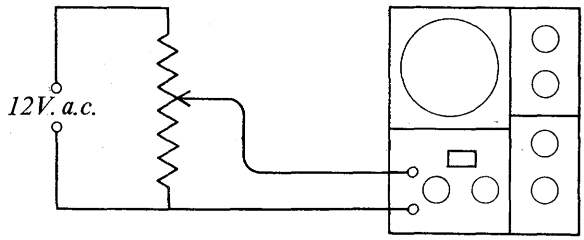


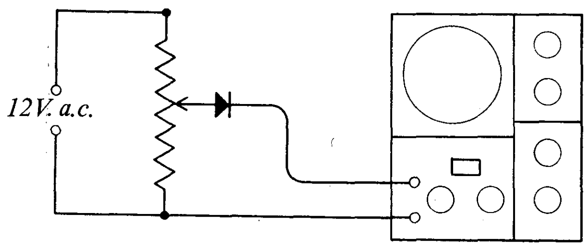
c. Show the shape of the 1000 Hz pulses from the scaler used earlier in this Year.



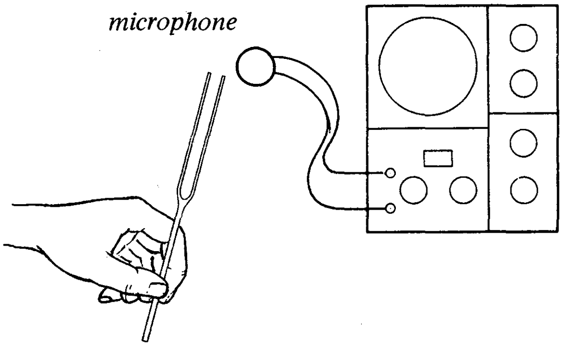
d. Measure a short time by sweeping rapidly and showing two sharp pulses on the trace, (e.g., speed of sound).

e. Illustrate the valve action of a solid-state diode.





f. And of course give pupils the pleasure of an 'acoustic mirror' to see the wave-forms of their own voice, or of any musical instrument that they play.



CHAPTER 12

OHM'S LAW AND OTHERS

Exploring Ohm's Law; using it in measurements; effects of temperature; changes of resistance; practical examples; non-linear devices

PROGRAMME

{By now, pupils should have a general acquaintance with simple electric circuits and measurements in them; and it is chiefly a question of making certain things explicit. We have settled on a definite, but arbitrary, amp (and a coulomb); and a definite volt, defined in terms of energy-transfer per coulomb, but measured in practice by a voltmeter which has simply been marked reliably.}

{We now make two uses of voltmeters and the p.d.s they measure.
(i) We look for relationships, in the behaviour of various conductors, between p.d. (perhaps thought of as a driving force) and current (perhaps pictured as a flow).
(ii) We calculate power- and energy-transfers (treating p.d. as energy-transfer per coulomb, and current as rate-of-flow of coulombs).}

{These two important topics are interchangeable in order. There is a slight advantage in dealing with p.d.: current characteristics first, because Ohm's Law can then be brought into power calculations at once. There is a slight advantage in dealing with energy and power first because they follow straight on from our introduction to voltmeters.}

Here we adopt the former choice.

VOLT: AMP CHARACTERISTICS. OHM'S LAW AND OTHER RELATIONSHIPS

How are potential difference and current related for an element of a circuit? In loose teaching language, how many amps does one volt drive through the sample; or, how many volts across the sample does one amp generate?

USES OF OHM'S LAW

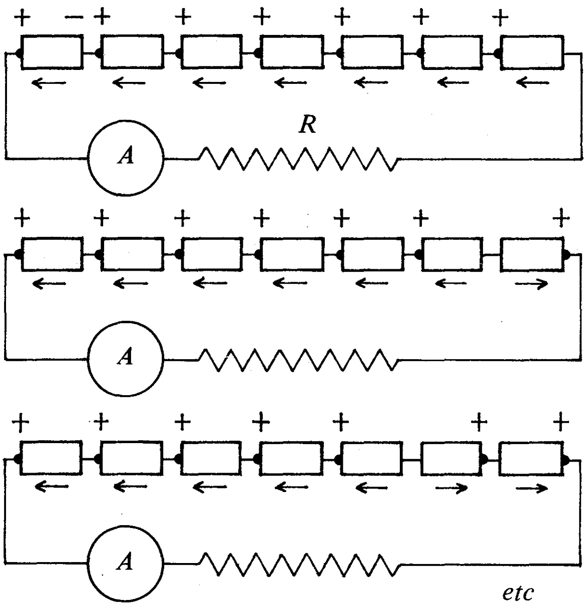
{**Some traditional uses may be omitted** Pupils should do some class experiments in which they use a voltmeter and ammeter to measure the resistance of something. It should, however, be a useful measurement and not just a formal exercise in measuring '*the resistance of the unknown coil*', or of '*the given pair of coils in series and in parallel*'. There is nothing wrong with those experiments and many a pupil rather enjoys making four measurements and then doing some interesting arithmetic with them to verify a formula. However, that work will not advance our programme into modern physics, so we urge teachers to omit it. In general, calculations using Ohm's Law should not be allowed to take charge and obscure experimental interest.}

Demonstration 112 Ohm's Law: a direct, simple approach—without a voltmeter

This is suggested as an approach to Ohm's Law in a quick demonstration. The electromotive force is provided by 7 1.5-volt cells all in series, all kept in the circuit throughout to maintain constant resistance. But the effective e.m.f. is varied by reversing 1 cell, 2, 3, ... all the cells—thus obtaining 8 points on a graph. Assuming that each cell exchanges the same amount of chemical energy with electrical energy for each coulomb, we use the algebraic total of cells as an ideal voltmeter reading! We plot that against the ammeter reading with a fixed resistance in the circuit.

Apparatus

7 1.5-volt cells, *new stock*	item 52B
(circuit boards, or other arrangement to hold the cells in series)	(52C)
2 rheostats (for constant resistance, 23 ohms)	541/1
1 demonstration meter	70
1 d.c. dial: 1 amp	71/1



Preparation

Test the cells beforehand to make sure they are all approximately equal—since pupils will need assurance of that. *Either* connect each in turn to a resistance of about 3 ohms and try a voltmeter across it; *or* arrange all the cells in series with about 23 ohms and try a voltmeter across each cell in turn. Replace any cell that fails to agree with the rest.

Procedure

Set up the circuit shown. Use two rheostats in series (23 ohms) to keep the current low; and restrict the time for which the current flows to a minimum.

Explain to pupils that we expect a coulomb to make the same interchange with chemical energy in every cell. Then we use the effective number of cells as a measure of the energy transferred to each coulomb.

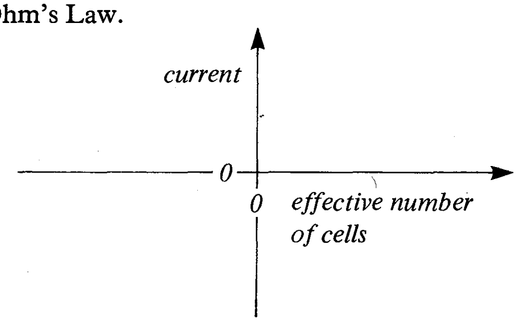
Explain that all the cells will remain in the circuit, to maintain constant resistance.

Record the ammeter reading with all 7 cells facing the same way.

Reverse one cell, and read the ammeter for what is now a 5-cell transfer.

Continue to reverse one more cell at a time until all 7 are reversed.

Plot a graph, which serves as an introduction to Ohm's Law.



The outcome Ask pupils what that suggests concerning current through the resistor and something we find from a tally of cells, something probably connected with energy-transfer, something perhaps measured by a voltmeter.

Then let them try making measurements with a voltmeter—with the simple graph as a tempting suggestion.

Ohm's work *Pupils' Text* mentions Ohm's search for a law regarding the 'resistance' which he had already imagined a wire must have—like the resistance a pipe offers to water-flow. It tells of his disappointment when the result was scorned, and of his happiness when it was finally recognised.

Then ask pupils to look at the behaviour that Ohm found.

NOTE ON LOGIC AND VOLTMETERS

Perhaps this is the moment to confer privately with teachers about the logic of using moving-coil voltmeters in an experiment to 'discover' or to 'test' Ohm's Law.

The question of logic about using them is not so important here as in many teaching programmes, because we do not stress Ohm's Law very strongly. Pupils meet the Law now in Year 4; but they will also meet materials and devices which have non-linear behaviour.

To make a practical moving-coil voltmeter we install in a box a high resistance which obeys Ohm's Law and a milliammeter to measure the current through that resistance. Then we label the meter's dial in volts.

If one constructs a voltmeter by putting inside it a high resistance that obeys Ohm's Law and a milliammeter to measure the current through that resistance, there may seem to be a threat of serious illogic if one then uses that instrument to test Ohm's Law. Many a teacher has been horrified on meeting this difficulty. And although he is very sorry to give up a good, simple, clear experiment, he has resigned himself to a demonstration with a much more mysterious electrostatic voltmeter; and he has comforted himself by expounding the logical difficulty to both pupils and colleagues.

In fact, however, that is unnecessary: it is carrying our logical worries much farther with voltmeters than we carry them in other cases. We never worry about using a stop-watch—whose balance wheel controls the reading of time by executing simple harmonic motion—when we test the S.H.M. of a pendulum or even a loaded spring. We use the watch and make perfectly good discoveries concerning S.H.M.

A full and careful logical examination of the statement that 'light travels in straight lines', or of the meaning of FORCE in Newton's First Law of Motion, can reduce a competent physicist to tears.

In practical teaching, where our aim is some sense of understanding, rather than a structure of rigorous logical building which we shall never achieve, we all of us have to leave out some of the argument and indulge in occasional loosening of logic—even our colleagues in mathematics do that, whether they are compelled to do so or not.

Here, we want to build up ability to use a voltmeter, knowledge of *what* it does—not minding too much *why* or *how* it does it—and some practical sense about volts, and amps, and then in turn about watts and kilowatt-hours.

Avoiding illogic Moreover, we do not have to take an immoral line in using a voltmeter. We can present it as a ready-made, closed instrument and assure ourselves of its behaviour by tests from outside—just as we can do for a stop-watch.

We do not open the instrument, we do not enquire into its interior, we do not reveal how it is constructed, we do not mention that it contains an Ohm's Law resistor; and none of these things matter because we can satisfy ourselves by experimental tests that this 'black box' does in practice measure the energy-transfer, between electrical form and other forms.

The crude test We do that first by making a crude overall test, connecting the voltmeter across 1 cell, then 2 cells, then 3, in series, acting on the basis of our trust in the Conservation of Energy. If we are not sure of that basis, we shall probably meet troubles* in discussing *any* form of voltmeter.

The full test Then our voltmeter can be tested at one or more points on its scale by a calorimetric method. Except in very skilful hands, with a lot of time given to careful corrections for heat losses, that method is so rough that one cannot call its results proper calibrations. However, this can serve as an *'experiment of principle'* to show how one *could* substantiate the behaviour of a voltmeter without opening it, and therefore without illogic. On account of the practical difficulties, we suggest that the calorimetric test should not be shown; but, instead, teachers should be ready to offer it to any pupil who wants to know the full story. It would not be wise to raise this hare with a whole class of pupils; but one should be ready to answer questions when any are asked.

Of course, we must be careful not to use voltmeter, ammeter, stop-watch, and calorimeter to measure 'J' in a class or demonstration experiment, if we are already using a calorimetric experiment—in practice or in imagination—to give validity to our voltmeter's scale!

Thus, there are several levels of knowledge at which we can put a moving coil voltmeter to use:

a. The unexplained and untested black box 'Here is a voltmeter. You connect it up like this; and you take the reading and multiply it by . . .' This produces at most the practical facility of some amateur radio enthusiasts, but no sense of understanding. As part of physics teaching, it is not good.

b. The black box with description of use and purpose by assertion This is an early level which we may have to use in teaching. We do not explain what is inside the voltmeter, but we do say clearly what it is intended to do. We discuss the idea of something called electricity or electric charge travelling round a circuit, to be measured in coulombs. We state clearly that 5 amps means 5 coulombs per second. (Thereby we are

---

* Of course such troubles are not inevitable, since there are ways of making mechanical measurements to assure ourselves that energy-conservation includes electrical forms of energy.

The basic experiment uses a Lorenz disc which can produce a voltage that we can predict from *mechanical* measurements together with an absolute measurement of current—though in practice that disc is used to produce a standard *ohm*, by making the current measurements cancel out.

There are other methods that use electrostatic devices, but these involve awkward measurements.

operating at this level *(b)* for coulombs, and perhaps only a little better for amps and ammeters.) We say clearly that the voltmeter tells us how much energy, in joules, is transferred *FROM* the electrical supply *TO* other forms, for every coulomb going through the part of the circuit to which we attach the voltmeter leads. At least its use is clear. This is the level at which we suggest introducing voltmeters in Year 3 or Year 4.

c. The black box turned grey by systematic external tests This is the treatment in which we give the overall test with several cells *and* just possibly, the calorimetric calibration. These are proof against any complaint of illogic on account of the resistor inside.

d. The 'secondary standard' treatment This changes the picture from a black box to a completely transparent box through which we can see the primary standard behind it. We simply say that this voltmeter does the job described at level *(b)*: (never mind how), because we make the marks on its scale by comparison with an ultimate standard.

Then we describe the ultimate standard at the National Physical Laboratory or elsewhere. In the case of a voltmeter the absolute standard is a combination of a current balance that weighs the forces between measured coils against known gravity-pulls, with a Lorenz disc which measures a standard ohm in terms of dimensions, and speed of rotation.

This is satisfying to much more advanced students but to describe it to young pupils is probably to produce a sense of insecurity, an impression that physicists let two of the passengers in the back seat hold the steering wheel.

e. Complete revelation We open up the voltmeter to show what has been done, throw it away as any kind of a theoretical standard, but go on making lots of voltmeters for practical purposes, happy that we now know how to choose the right resistance to add to the milliammeter to make the instrument we want.

Such a theoretical throwing away is a good move for an advanced physicist, though it should not be accompanied by unjustified celebration, or condemnation of levels *(b)* etc. The business of making a voltmeter is an interesting experiment and important practical engineering.

This note is not intended to suggest any discussion of these matters with pupils in O-Level Years.

Class Expt 113 Ohm's Law

Although Ohm's Law is no longer the cornerstone of elementary practical electricity, pupils should have personal experience of testing it and enjoyment of finding a simple relationship by their own experiment. Therefore they should work in pairs rather than in the larger groups which resources of equipment might seem to dictate. For this Year, we expect sufficient ammeters (0–1A) and voltmeters (0–5 V *and* 0–15 V) to be available; so it is only rheostats that impose a limitation—eight (10 to 15 ohms) were required in the first edition. We hope schools can provide 8 more—robust rheostats* are 'kitchen equipment' with many uses in a modern lab.

Otherwise, we suggest that some pairs (or all) should dispense with the rheostat and just use several different voltages tapped from a 12-volt battery. In one way that is even better: it leads to a compelling linear graph through half a dozen points and avoids the risk of the simplicity being masked by a long tedious set of measurements. With this method, points for just 0,2,4 volts would hardly be convincing. Measurements should continue with one or two more cells. The limit is imposed by the heating of the wire—in which case use a longer sample—or by the ammeter's range—in which case use the 0–5 amp range of item 178.

* We do not suggest buying cheap radio resistors—they are apt to lead to flickering meter readings. Nor, for the same reason does a taut Eureka wire with movable clips seem advisable—also it might be confused with the specimen wire.

Apparatus

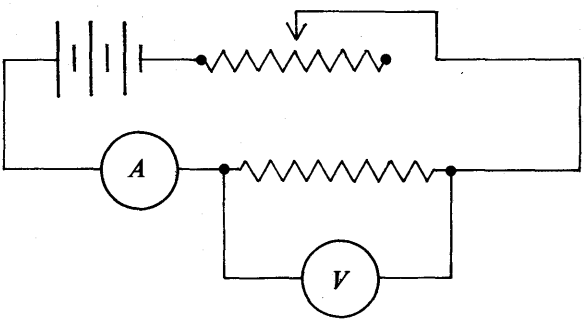
16 d.c. ammeters (1 amp)	item 79 (or 178)
16 d.c. voltmeters (0–5 V, 0–15 V)	179
20 lengths of Eureka wire, s.w.g. 34 (10 cm to 20 cm,‡ according to voltage and voltmeter scale chosen)	52P
16 rheostats (10 to 15 ohm), or alternatives‡	
16 d.c. supplies‡	541/1

‡ See the discussion above. The d.c. supply may be several 1.5-volt cells from the Worcester circuit board kit, or several cells tapped from a car battery (item 176)—in which case several pairs can share one battery.

Pupils work in pairs.

Preparation

Since labs differ in equipment, it is important to try out this experiment beforehand and choose the length of sample and the voltmeter range.



Procedure

Ohm's Law: measurements Give pupils a sample wire of an alloy with small temperature-coefficient. Ask them to take readings of an ammeter in series and a voltmeter across the sample.

Then each should plot a graph.

Pupils follow these instructions:

* * * * *

Set up the circuit shown.

Obtain a series of pairs of readings of the CURRENT through the sample of alloy wire and the VOLTAGE across it. Three or four pairs will be enough, but they should spread from 0 to the largest value your instruments can take.

How do current and voltage seem to be related, for your wire?
(i) First guess by looking at your measurements. Then test your guess by arithmetic: divide p.d. (voltage) by current.
(ii) Plot a graph of p.d. (upwards) against current (along). *What does your graph tell you?*
(iii) We call P.D./CURRENT the RESISTANCE of the sample.

Calculate the resistance of your sample from your arithmetic in *(i)*. Your answer will be in $\frac{\text{volts}}{\text{amps}}$ or *volts per amp*. We name one *volt per amp* one *ohm*—this is just dictionary-work to be economical, like naming one *sea-mile per hour* one *knot*.
(iv) Also calculate the resistance from measurements of your graph. *In what way does the graph give you a better estimate?*

* * * * *

After the experiment, tell pupils that the rule or behaviour that we now name Ohm's Law is this: 'the graph of p.d. plotted against current is a straight line through the origin. That is characteristic of those conductors which 'obey' Ohm's Law and are called '*linear devices*'.

Logic and use of a moving-coil voltmeter to test Ohm's Law See the box for a note on *Logic and Voltmeters*.

Questions for thinking and discussion in class Some questions should be raised (but not answered).

1. What is the meaning of Ohm's Law, in terms of something like water flow?

2. What would happen to the heating in an Ohm's Law wire if we doubled the current? (It would be a pity to give a ready-made formula for the heating. Encourage interested pupils to argue their way through to the idea that doubling the current would double the voltage, and therefore the heat would be quadrupled.)

3. Perhaps ask pupils what they think happens to electrons as they are driven through the wire; and what the Ohm's Law behaviour tells us in terms of electron motions—though that is liable to lead to difficult arguments.

A note to teachers: importance of Ohm's Law {We urge teachers to spend much less time than has been customary on Ohm's Law—in experiments, measurements, and calculations—and to make sure that pupils meet other things which do not 'obey' Ohm's Law.}

{As a practical rule, Ohm's Law assumed great importance in the last century when telegraph lines were being designed and installed and balanced, and electrical engineering was growing up. Nowadays Ohm's Law does not receive so much attention. We still regard it as an important description of the behaviour of some materials, and we still use it for some calculations; but the training of modern scientists and engineers does not lay much stress on it.

Series and parallel resistances are used; an engineer must be able to calculate them but he learns that quickly when the need arises, so the traditional emphasis in school teaching is hardly necessary. Calculations of arrays of cells in series and parallel are quite unnecessary: they date from the early batteries in the last century, when large internal resistance required such arrays.}

{Modern electric circuitry makes transistors and other non-linear devices as important as the linear ones that 'obey' Ohm's Law. Also, many modern routine measurements are made with multi-meters rather than bridges. (The Wheatstone bridge fell out of use generations ago, except in teaching laboratories. In standardising laboratories, most resistances are 'four-terminal' devices, to be used in potentiometer measurements. Therefore, a Wheatstone's Bridge should *not* be offered as a practical example of using Ohm's Law in everyday life—we should *not* keep it in our school programme.)}

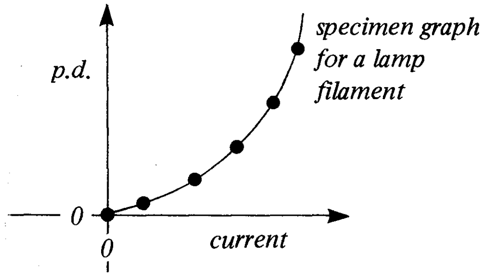
{So our work here with Ohm's Law should be treated lightly and not made the cornerstone of a great electrical edifice. It is only a particular case, applying to *some* conductors; and pupils should investigate other behaviours too. In this century it is the non-linear devices that have enabled us to make great advances: valves, transistors, rectifiers, etc.}

{Of course, Ohm's Law has also been given importance in teaching because it is a simple law. In developing physical science all of us look for simple linear relationships first and are pleased if we find them. But now it is time to take a wider view.}

Examiners will not be tempted to set a profusion of Ohm's Law problems.

TEMPERATURE CHANGES

Tell pupils that some materials which *appear* not to 'obey' Ohm's Law would show Ohm's Law if we kept their temperature constant; for example, pure metals such as the tungsten of a lamp filament.



Pure metals do 'obey' Ohm's Law but their resistance grows with heating; it is roughly proportional to absolute temperature. The wires that pupils use to examine 'Ohm's Law behaviour' are special alloys, with exceptionally small temperature coefficient (e.g. 60% copper and 40% nickel). We should feel rather guilty if we based an extensive investigation on experiments with such special materials and claimed a far-reaching result without explanation.

Give pupils a small open coil of *copper* wire which, as they will find, yields a curve. But if they keep the copper wire cool in a large bath of water, very well stirred, they will probably believe that the deviation from a straight line may be due to temperature changes.

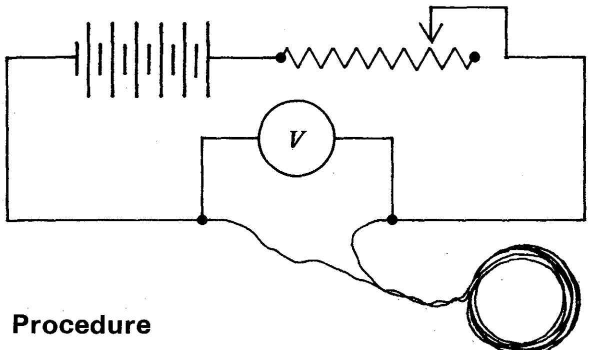
Class Expt 114 Temperature-change and resistance

Apparatus

Note that only a shortage of rheostats prevents pupils from working in pairs.

4 (or more) 12-volt batteries	item 176
8 rheostats (10–15 ohms)	541/1
8 aluminium containers	76
8 d.c. ammeters (0–5 amp)	178
8 d.c. voltmeters (0–12 volt)	179
8 coils of copper wire‡	(222)

‡ Each coil is made of 1 metre of SWG 32 enamelled copper wire.



Procedure

Pupils follow these instructions.

* * * * *

a. Set up a simple series circuit with long leads joined to the loosely wound coil of copper wire.

Adjust the rheostat to give a current about 4.5 amps through the coil. Then switch off.

After a minute or so (for cooling) switch on and read the ammeter and voltmeter during the next half-minute or so. Watch the changes.

b. Repeat the experiment with the coil suspended in water in the container. Keep the water very well stirred.

* * * * *

CONDUCTION BY IONS IN LIQUIDS AND GASES

Show, or let pupils try, the effects of a current through conducting liquids: copper sulphate solution and (now or in Year 5) water.

a. Copper sulphate solution with copper electrodes This was suggested in Chapter 11 as possibly helping pupils to understand the concept of coulombs—by regarding copper plating as coulomb-counting. A coulomb could sometimes be pictured as a large charge of electricity riding across on a host of doubly charged copper atoms. So pupils may have met the experiment already. If not, they should meet it now, as an example of another type of conduction.

When they see the current flowing, as shown by the ammeter, and find copper is being deposited on the cathode plate, pupils are apt to think of copper ions tearing across at great speed to carry that current. In fact the ions' motion is a very slow drift, added to all the rapid thermal motions. The current is large because the carriers are very numerous, not because they are speedy.

The liquid is populated with such ions: and, as the current continues, charges continue to leave the anode and charges continue to arrive at the cathode. But each individual ion takes an enormous time to drift across. Yet, since the drift starts as soon as a p.d. is applied the current appears to 'travel' very fast.

We should warn pupils that in a conducting solution the metal ions may not be the only carriers: there may well be ions of opposite signs which drift the opposite way when a p.d. is applied, and thus share in carrying the current.

b. Water with acid added, with inert electrodes This is *OPTIONAL NOW* since it is important in Year 5 when we use a measurement of the hydrogen evolved in comparing the masses of electrons and protons, so it may well be postponed until then.

If the electrolysis of water *is* shown now, it will be best to use the same method for both water and copper sulphate. Electrolysis of water is unnecessarily confusing if a rheostat is used. Instead a selection of voltages should be applied by tapping the battery: 2 volts, 4, 6, ... The graph of voltage against current will be a fairly straight line starting from an initial point between 1 and 2 volts.

Copper sulphate solution will give a graph that is a straight line through the origin—Ohm's-Law behaviour.

c. Metals This may be the time to mention the motion of electrons in metals. In giving a very simple picture we say that a metal atom has one or two 'free' electrons which can be driven by a p.d. and travel through the lattice of positive cores—or perhaps, stagger from core to core. In the absence of an applied p.d. those electrons are anyway in rapid random motion—unexpectedly rapid, far faster on the average than one would expect for gas molecules of their mass. Then an applied p.d. (which makes a driving field) only adds a slow drift to those random motions.

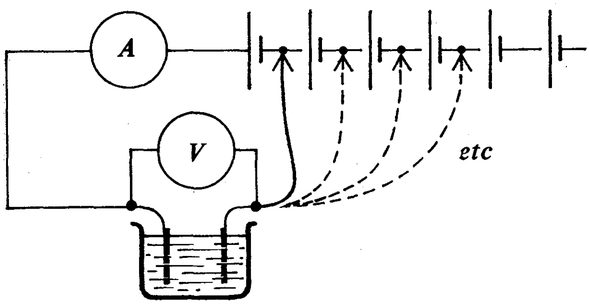
Demonstration 115 Relationship between volts and amps for copper sulphate solution

Apparatus

1 12-volt battery‡ (or 6 2-volt cells)	item 176
2 demonstration meters	70
1 d.c. dial: 1 amp	71/1
1 d.c. dial: 15 volt	71/10
1 copper voltameter	153
copper sulphate	
sulphuric acid	
distilled water	
(rheostat‡ 10 to 15 ohms)	541/1

‡ The electrolysis of water needs to be done in a special way to avoid confusing effects of polarisation: apply a series of voltages tapped from a battery, and avoid using a rheostat. If electrolysis of water is to be shown immediately after this copper experiment it will simplify the teaching if the same method is used here. (If the currents are too big for the ammeter, a *fixed* resistance can be inserted in series, but the voltmeter should be across the copper voltameter alone).

If a 12-volt battery (item 176) is used, it must be such that it is possible to tap off intermediate voltages in steps of 2 volts. Some recent types make that difficult. However, some manufacturers supply batteries adapted for school use, and these are recommended.



Preparation

For the electrolyte add a few drops of sulphuric acid to saturated solution of copper sulphate.

Find by trial beforehand whether a fixed resistance in series is needed.

Procedure

Connect the copper voltameter in series with the ammeter (and fixed resistor if needed) to the battery, with the voltmeter across the voltameter. Make measurements of voltage and current with 1 cell, then 2, 3, 4, 5, 6 cells. Plot a graph.

Demonstration 116 Relationship between volts and amps for water
(OPTIONAL NOW)

Apparatus

1 12-volt battery‡	item 176
2 demonstration meters	70
1 d.c. dial: 1 amp	71/1
1 d.c. dial: 15 volt	71/10
1 Worcester gas voltameter kit	54
sulphuric acid	
distilled water	

‡ See the note in the previous demonstration about using a tapped battery.

Preparation

Add a few cm^3 of sulphuric acid to the jar full of water. Fill the apparatus (see page 197).

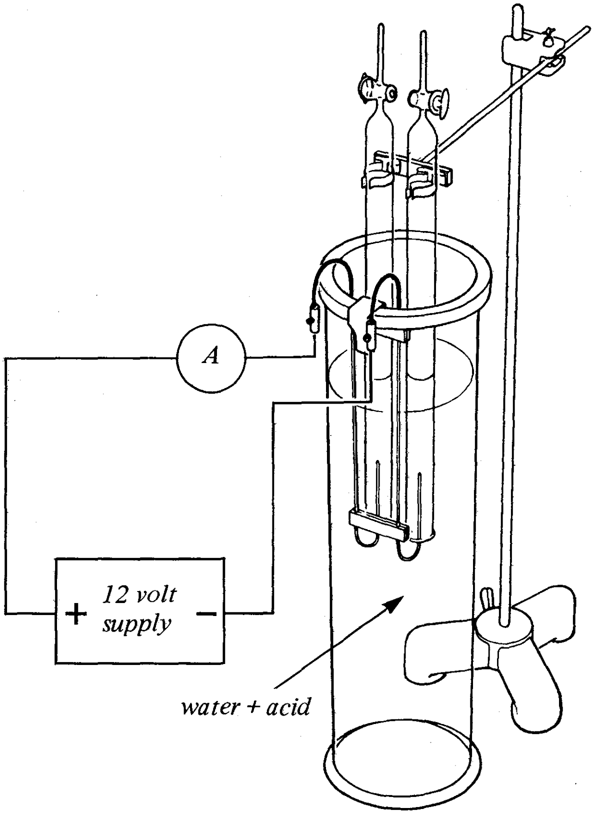
Procedure

Connect the gas voltameter in series with the ammeter to the battery, with the voltmeter across the voltameter.

Make measurements of voltage and current with 1 cell, then with 2, 3, 4, 5, 6 cells.

Explain that the acid is only added to provide plenty of hydrogen ions to carry current. The same amount of acid is left over at the end; the gases are produced at the expense of some of the water.

Discuss the failure of the graph to pass through the origin.



Gases Air and other gases are good insulators—even better when compressed. Only when strong electric fields detach electrons and make more ions by collision do gases conduct.

Give a demonstration of a current passing through a gas. The easiest sample is a neon lamp, which should be run on a d.c. supply. This does not sound so grand as a 'discharge tube', yet the latter is only a qualitative show, offering no chance of useful measurements.

Here we only want to show that a gas *can* carry a current in some circumstances; so we should not stress the complexity of affairs inside the lamp.

This provides an important piece of knowledge (which might also be inferred from behaviour of some street lamps). The knowledge contributes to atom models, so it is needed for Year 5. *Therefore we do not suggest this should be optional.*

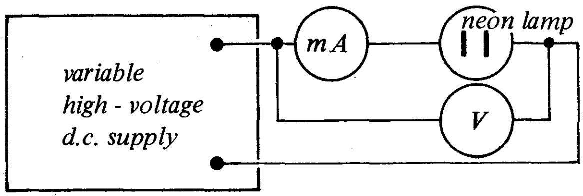
Demonstration 117 Relationship between volts and amps in neon gas

This is a quick experiment, easily shown. Unfortunately, obtaining a suitable neon lamp is not easy: the styles available change from year to year so teachers will need to adjust the current range to the local style.

Apparatus

1 neon lamp (e.g. 240 volt, 5 watt)	item 66
1 lamp holder (B.C.) on base	162
1 H.T. power supply	15
2 demonstration meters	70
1 d.c. dial: 300 volt	71/11
1 d.c. dial: 100 mA	71/12
1 voltage divider‡	

‡ If the voltage of the d.c. supply can be varied from 0 to 240 volts, no voltage divider is needed. If the supply is fixed at 240 volts a rheostat must be installed as a potential divider.



Procedure

Set up the circuit as in the sketch. Connect the voltmeter across the lamp *and* 100-mA meter.

Apply increasing voltages from 0 to 240 volts and record both the current and the voltage. Then decrease the voltage again.

Notes

1. To prevent excessive currents, most neon lamps are provided with ballast resistors in the base (e.g. about 2000 ohms).

2. As the voltage is raised, a glow will start abruptly. When the glow is established, the total p.d. across the lamp *and* its internal ballast resistor, will be about 170 V. The glow will grow with further increase of applied voltage. When the applied voltage is reduced the glow will be extinguished at about 150 V.

3. The striking voltage is likely to be higher if the lamp is in darkness, and lower if it is irradiated with gamma rays. (Lamps intended for lower voltage supplies may be doped with a weak ionising agent.)

OTHER MATERIALS: OTHER BEHAVIOURS?

Programme Pupils should measure p.d. and current for some other things, which do not show Ohm's Law behaviour: such as some form of transistor. We should let them make their own discoveries without any warning of the peculiarities to be expected.

As an introduction, we suggest simple class experiments on effects of temperature changes. These are *not* suggested as a basis for systematic notes on temperature effects—at this stage those effects are not very important in themselves; any formal study of them should be left to A-Level. So, *unless these can be informal experiments (in which pupils are given encouragement but not much help) they should be omitted.*

Temperature effects The following class experiments and demonstrations (118–122) show how various materials change their conductivity with change of temperature. The class experiments are intended to be 'open' investigations. They present technical difficulties for a pupil to surmount. They could be optional, except for fast groups.

Class Expt 118 Effect of temperature changes on conductivity

Apparatus

Since it is likely that only some pupils will try these, the list below shows apparatus needed *for each pair*.

For a large group, 12-volt batteries can be shared, one battery feeding four pairs in parallel.

Apparatus

1 12-volt battery	item 176
1 coil bare copper wire (1 metre, SWG 32)	2B
1 coil bare Eureka wire (1 metre, SWG 28)	98
1 d.c. ammeter, 0–1 amp	97
1 test tube containing some paraffin wax	560
1 bunsen burner	508
salt	567
ice	
1 thermistor	132/N
glass rod (10 cm)	561
thick copper wire (about SWG 14)	222/4

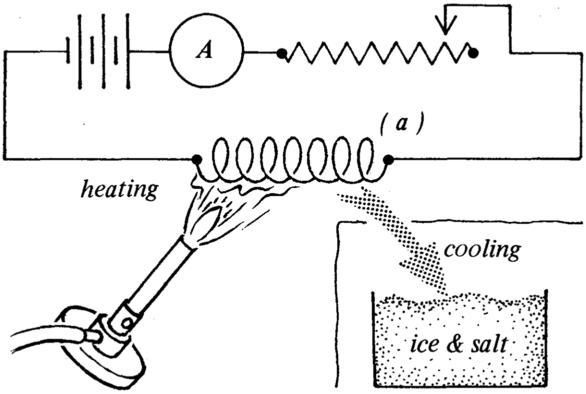
Procedure

Pupils follow these instructions.

★ ★ ★ ★ ★

Try the effect of heating on some materials which may conduct a current.

Set up a circuit with battery, rheostat, ammeter and the specimen. Heat the specimen gently with hot water or even a small flame. (If you like try the effect of cooling with ice.) Try some of the following specimens.



a. Thin bare copper wire—about 1 metre made up into an open coil.

Adjust the rheostat or the battery connectors to make the current about 0.8 amp. This will need only a small voltage.

Then warm the copper coil *very gently* in a low bunsen flame. Watch the ammeter.

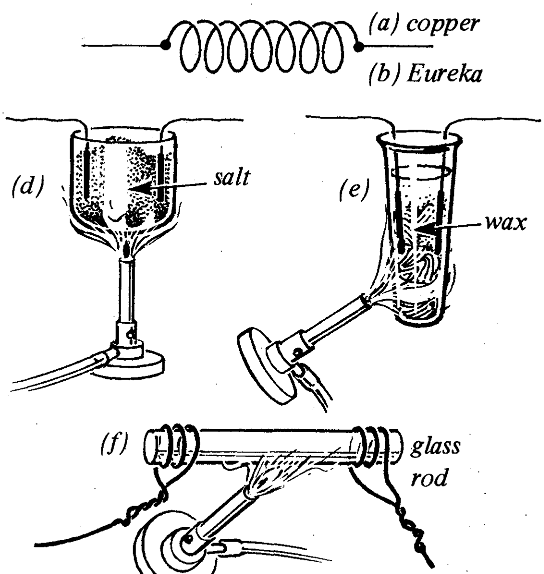
If you like, extend the experiment by placing the coil in a mixture of ice and salt, or in some solid CO_2.

The resistance of copper clearly increases as the temperature is raised. *What use might be made of this effect?*

b. Replace the copper coil by a coil of alloy wire (Eureka: 60% copper 40% nickel). Repeat the experiment. You will need a greater voltage.

Interesting optional extensions

c. Try a thermistor instead of the coil. Warm it gently.



d. Put a block of salt in a crucible. Dip two pieces of thick bare copper wire into the salt and connect them in the circuit, in place of the coil. Heat the crucible *gently*. Watch the ammeter.

e. Embed two pieces of thick bare copper wire in paraffin wax in a test tube. Make sure they do not touch. Then connect the pieces of wire in the circuit.

Heat the tube *gently*. Watch the ammeter. (*Hint*. Remember that 0 is a perfectly proper number among measurements!)

f. Try a glass rod about 10 cm long. Wind two or three turns of thick bare copper wire round the glass rod near each end. Connect the wires in the circuit.

Heat the rod *gently*. Watch the ammeter.

(You may see a glass rod being heated much more strongly in a demonstration with a large mains voltage across it. If it is hot enough it will behave differently.)

★ ★ ★ ★ ★

Demonstration 119 The effect of strong heating on common salt and paraffin wax

Apparatus

1 12-volt battery	item 176
1 demonstration meter	70
1 d.c. dial: 1 amp	71/1
1 rheostat (10–15 ohms)	541/1
1 small crucible	
1 pipe-clay triangle	
1 tripod	511
1 Bunsen burner	508
salt	567
paraffin wax	560

Procedure

a. Place a little salt in the bottom of the crucible. Support two stiff copper wires so that they reach the bottom of the crucible and make electrical contact with the salt. Connect up the circuit.

After showing that the solid salt does not conduct, remove the electrodes from the salt—they conduct heat away too fast—and heat the crucible strongly until the salt melts.

Replace the electrodes. Adjust the rheostat to make the current about 1 amp. Remove the burner and allow the salt to cool. The current soon falls to zero.

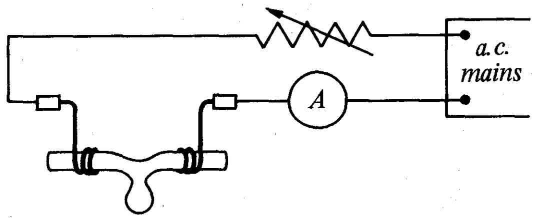
Mention the use of molten salt's conduction in the extraction of sodium metal. Remind pupils that common salt dissolved in water makes a conducting solution. Perhaps electrically charged carriers (Na^+ and Cl^-) are already there in solid crystals of salt, but locked in too tightly to travel.

b. Repeat the experiment using paraffin wax instead of salt. Show that paraffin wax, unlike salt, fails to conduct even when melted.

Demonstration 120 Current in a heated glass rod

The sodium ions in the glass rod carry a current when the glass is fluid enough to let them move, and the heat developed as that current is driven through the resistance of the rod (which is still quite high) is sufficient to carry the glass up to melting point.

The demonstration is much easier to set up and run than the long instructions below might suggest. It is a remarkable sight when the glass becomes soft enough to let the ions in it carry current; the current then maintains the heating, which increases until the glass melts and drips.



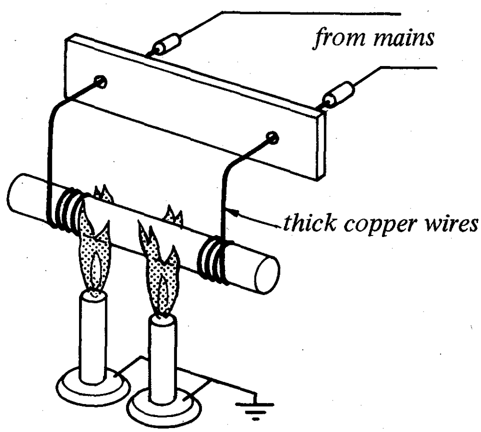
Apparatus

1 demonstration meter	item 70
1 a.c. dial: 5 amps	71/7
2 20-cm lengths bare wire, copper, SWG about 14	
1 length soft glass rod (soda glass, 6 to 8 cm long, 7 to 12 mm diam.)	305
1 or 2 retort stands	503/4
1 or 2 bosses	505
1 limiting resistor (e.g. radiant heater, item 58C)	
2 Bunsen burners	508
strip, or two tubes, of insulator	
protecting mat for table	

Procedure

Wind two tight coils, each of three or four turns of the thick bare copper wire, on the glass rod at places 3 to 5 cm apart. The rod must be of soda glass.

Support the wires by a strip of insulating material which is held by a clamp on an earthed retort stand. The wires should terminate in 4-mm plugs while the main leads terminate in 4-mm sockets.



Arrange the glass rod at such a height above the bench that a bunsen flame can reach it and heat it strongly.

Cover the bench top below the rod with a heat resistant mat.

Connect the two thick wires in series with the limiting resistor (e.g. a radiant heater) and the 240-volt a.c. mains.

Great care is needed with this circuit. The retort stand and the bunsen should be earthed.

An a.c. ammeter (0–5 amp) may be included.

Switch on. (No current flows.)

Heat the glass rod strongly with a bunsen flame for 2 or 3 minutes. There may be tiny sparks at the contacts between the wire coils and the glass. Soon after that the glass will start to glow dull red; it is conducting and the heat generated by the current will then suffice. Then remove the flame. Pupils watch the rod slowly redden and melt. Switch off.

Demonstration 121 The effect of strong heating on a thermistor
(BUFFER OPTION)

Thermistors are made of a mixture of metal oxides, such as those of copper manganese and nickel. They are classed as semi-conductors and their resistance decreases with temperature rise.

Apparatus

1 12-volt battery	item 176
1 demonstration meter	70
1 d.c. dial: 1 amp	71/1
1 thermistor‡	132/N
1 bunsen burner	508

‡ Radiospares thermistor type TH3 has a cold resistance of 400 ohms and a hot resistance of 28 ohms.

Procedure

When the thermistor is cold, the current will not be detectable with the meter.

Heat the thermistor *very* gently with a low bunsen flame and the current will start to rise.

Stop the heating when the current reaches 0.3 amp, or the thermistor may be damaged.

Demonstration 122 Conductivity of germanium *(OPTIONAL)*

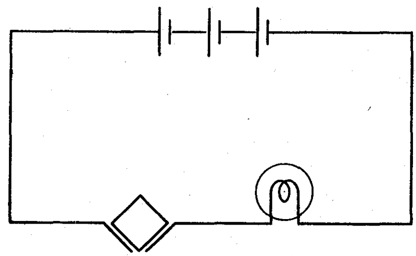
Pure germanium is called an intrinsic semi-conductor. It behaves rather like an insulator at low temperatures. As the temperature is raised it suddenly becomes quite a good conductor—at a temperature far below the temperatures of breakdown or melting at which most insulators become conducting.

Apparatus

3 1.5-volt cells	item 52B
(a circuit board may be used to hold the cells, item 52C, E)	
1 6-volt 0.4 amp M.E.S. lamp	306
1 M.E.S. lamp holder	92T
1 mounted slice of germanium	132P
1 small soldering iron	

Procedure

Connect the mounted slice in series with three cells and the lamp. The lamp does not light. Then heat the slice by touching it with a small soldering iron (25 watt) or any small block of metal that has been heated gently. The lamp will light.



Notes

1. The germanium slice (n type) is 5 mm square, 1 to 2 mm thick, and has leads soldered to two adjacent edges. The resistance cold is of the order of 300 Ω.

2. With some specimens larger voltage may be needed to give a good effect.

3. A match flame is liable to melt the solder. With a slice that has soldered leads, touching with a hot tool like a soldering iron has proved to be the only method that is easy and safe.

These experiments suggest that, instead of our original division of solids into two groups: conductors and insulators, we now may have to include two other groups: semi-conductors, which appear to pass no current at low temperatures, but readily conduct at higher temperatures; and solid electrolytes, which do not appear to pass a current until they are almost melting.

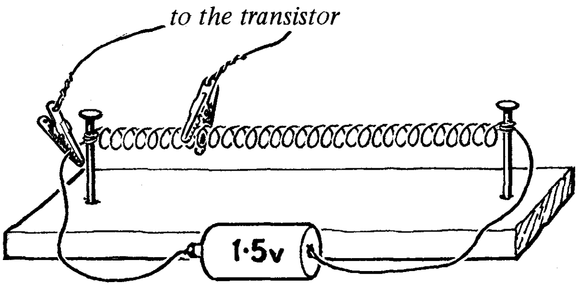
Transistor class experiment Pupils should do at least one experiment with transistors; but we should not attempt any explanation of the mechanism of transistors unless pupils ask for it—and even then we should give only a simple picture.

Class Expt 123 Transistor

AIM: to let pupils use a transistor and see what it can do.

In the example chosen, a minute current in the base-emitter circuit is used to control a much larger current in the collector-emitter circuit.

In the first edition, we suggested this as a demonstration, because it used an expensive rheostat as voltage-divider. Since transistors are now cheap as well as important we consider this must be a class experiment.



a home-made voltage divider

Voltage-divider The transistor needs a small voltage to cause base current to flow: less than 1 volt. That is easily obtained from a voltage-divider ('potentiometer') across a cell; but that makes a great difficulty for beginners because *the voltage-divider looks like a rheostat.* (Even at a much later stage, some students fail to understand the voltage-divider and make damaging mistakes.)

The only recourse we suggest here is: avoid using a rheostat (or, more confusing still, a radio 'pot') and provide instead *an open home-made voltage-divider for each group of pupils.*

That should be a taut wire, or a closely-wound spiral, of Eureka or Nichrome, stretched between two posts, with a wandering lead and crocodile clip to tap off a small p.d. (A replacement spiral for heater elements does well. Use half the length.) In any such form, 'taking a fraction of the voltage' may seem more obvious—like slicing out a fraction of a cake. It will even look like its picture in a circuit diagram.

The input voltage to the transistor is not very small. $V_{input} = I_b R + V_{be}$. With the transistor suggested, the base-emitter voltage, V_{be}, is about 0.7 volt when the transistor is conducting milliamps, and it does not change much. For $I_b = 0.5$ mA and $R = 680$ ohms, V_{input} is about 1 volt. Then, if the transistor has a gain of 100, the collector current would be 50 mA and the 6-volt lamp would be 'fully' lit. Zero base current occurs when $V_{input} = V_{be} = 0.5$ volt approx. (That is the p.d. needed to make the base-emitter 'diode' conduct). Thus V_{input} needs to be varied from 0.5 V to 1.0 V. (Note that the range of input voltage needed depends on the magnitude of R).

Apparatus

8 transistors (silicon npn ZTX 300‡‡ or 2N 3705)	item 132M
16 galvanometers (3.5–0–3.5 m.a., 10 ohms)	180
16 resistors, approx. $\frac{1}{2}$ ohm for shunts‡	
2 to 8 12-volt batteries (to provide 6V)	176
8 U2 dry cells	52B
8 resistors (680 ohms, 1 watt)	132G
8 M.E.S. lamps (6 volt, 60 mA)‡	221
8 M.E.S. lamp holders	92T
8 home-made voltage dividers‡‡‡	

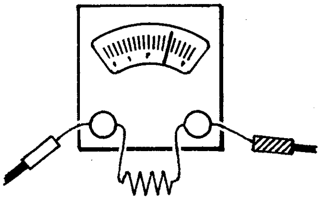
‡ The lamps and shunts are new Nuffield items for this experiment. The lamps fit existing holders. The shunts are used to make *both* galvanometers read to a maximum between 90 and 100 milliamps. Home-made ones are best: pieces of Eureka wire with a loop at each end. They need not be tailored to an exact value, but the two that a pupil uses should make his galvanometers match roughly.

‡‡ The transistor has the old item number, 132M, but the one now suggested is a more suitable type than the OC.81 suggested in the first edition. Note that the batteries in the new circuit are reversed from their positions for OC.81.

‡‡‡ The voltage-divider is, as suggested above, a long coil (or possibly a straight wire) of Nichrome or Eureka, of resistance 10 to 20 ohms, anchored at each end. A movable lead with a crocodile clip provides a variable tap on the wire.

Preparation

Make simple shunts of Eureka wire, connecting them across each galvanometer and adjusting the length to make the maximum reading between 90 and 100 milliamps. The best method of attaching such a shunt depends on the style of terminals. (The *safest* way is to extend the shunt wire beyond the basic instrument's terminals and ask pupils to connect to the extensions, as in the sketch. Some will meet this in constructing an ammeter.)



Procedure

Explain to pupils the general idea of the voltage divider: to provide a small voltage sliced out of the 1.5 volts of the cell.

Arrange the circuit as in the sketch. Connect the voltage divider across the $1\frac{1}{2}$-volt cell.

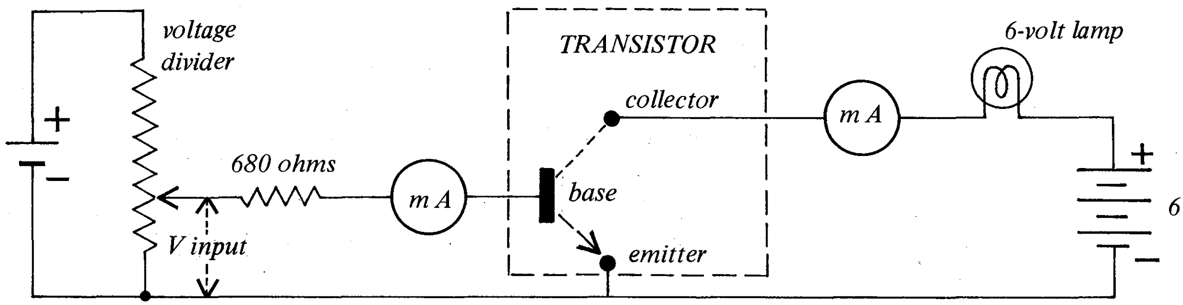
Connect the movable clip to the fixed resistance of 680 ohms, one galvanometer (range about 100 milliamps) and the *base* terminal of the transistor.

Connect one end of the voltage divider to the *emitter* terminal of the transistor.

Connect the *collector* terminal of the transistor to the other milliammeter (range about 100 milliamps) the small lamp and the 12-volt battery and back to the *emitter* (which is already connected to the voltage divider).

Try the following experiments:

(i) Leave the base circuit open, with no connection to the base. You will see no detectable current in the collector circuit.
(ii) Join up the base circuit. The voltage for a suitable base current is less than 1 volt. Start with no voltage from your voltage-divider and increase the voltage until the lamp in the collector circuit glows. Read the milliammeter in that circuit.



Then pupils follow these instructions:

* * * * *

A transistor is a tiny chip of semi-conductor materials. It is rather like a sandwich of a slice of ham between two slices of white bread.

The transistor's emitter corresponds to a THIN SLICE OF BREAD.
The transistor's base corresponds to the HAM.
The transistor's collector corresponds to a THICK SLICE OF BREAD.

In your transistor, a minute current in the base-emitter circuit is used to control a *much* larger current in the collector-emitter circuit.

Then look at the other milliammeter, in the base-emitter circuit. *Is any current flowing to the base?* If there seems to be *no* current try switching the supply on and off, and see whether the milliammeter's pointer moves at all.

Your transistor is amplifying current. Comparing the two milliammeter readings gives you an idea of the amplification.
(iii) Increase the *base current* a little, causing an increase in *collector current.* The ratio of the two currents will remain approximately constant.
(iv) The collector current will level off at about 60 milliamps, which is the limit imposed by the lamp in the circuit. Any further increase in the base current will have no further effect.

* * * * *

USEFUL RESISTANCE MEASUREMENTS

Pupils should measure the resistance of some common things with voltmeter and ammeter.

(As a puzzle one might even ask some pupils if they can measure the resistance of their own voltmeter—this will open up an interesting squabble among able pupils.)

Class Expt 124 Measuring resistance with a voltmeter and an ammeter

Apparatus

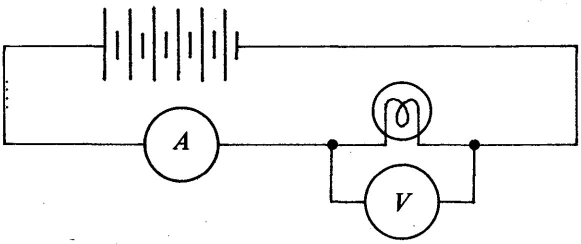
16 d.c. ammeters (0–1 amp)	item 79
16 d.c. voltmeters (0–15 volt)	179
4 (or more) 12-volt batteries	176
16 S.B.C. lamp holders	74
16 lamps (12-volt, 6 watt)	177
16 radio resistors (15 ohms, 10 watt)	132F
4 radiant heaters	58C

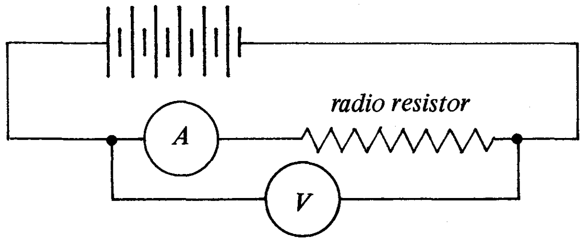
Procedure

Pupils follow these instructions.

* * * * *

(i) Resistance of a lamp. Set up a circuit as shown. Take one pair of readings of the ammeter and voltmeter. Calculate the resistance of the lamp *at its running temperature*.





(ii) Resistance of radio type resistor. Replace the lamp in the circuit by a radio resistor. (Beware of including the voltmeter's current in the ammeter's measurement.) Repeat the measurements and calculation.

(iii) Resistance of heating element of an electric fire. Repeat the experiment with a radiant heater element. Use 12 volts.

* * * * *

After this has been done as a class experiment, the teacher should measure the resistance of the element on 240 volts (a.c. or d.c.). See the following demonstration.

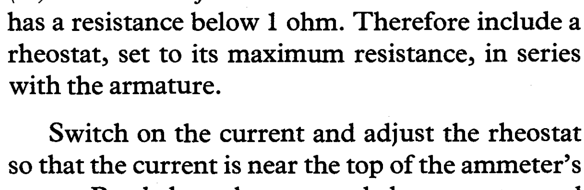
Demonstration 125 Measuring resistance

Apparatus

1 fractional horsepower motor	item 150
1 radiant heater	58C
1 12-volt battery	176
1 rheostat (10–15 ohms)	541/1
2 demonstration meters	70
1 d.c. dial: 1 amp	71/1
1 d.c. dial: 15 volt	71/10
1 a.c. dial: 300 volt	71/9
1 a.c. dial: 5 amp	71/7

Procedure

(i) Heating element of an electric fire. After pupils have measured this in a class experiment, measure the resistance of the element on 240 volts, a.c. (or d.c.). Use the demonstration meters to measure the current (about 2 amps) and the voltage. (*Note:* The temperature coefficient of nichrome wire is quite small.)



(ii) Resistance of motor armature. The armature has a resistance below 1 ohm. Therefore include a rheostat, set to its maximum resistance, in series with the armature.

Switch on the current and adjust the rheostat so that the current is near the top of the ammeter's range. Read the voltmeter and the ammeter and calculate the armature resistance.

The resistance of the field coils can be determined in the same way: in this case an ammeter reading of about 0.5 A will be suitable.

Expt 126 Advanced puzzle: Measure the resistance of a voltmeter itself

(OPTIONAL BUFFER EXPERIMENT)

This should be given as a problem to pupils without any instructions.

Apparatus

Since few pupils are likely to try this, the list shows the apparatus needed for *each pair*.

1 galvanometer	item 180
1 d.c. voltmeter (0–15 volt)	179
1 12-volt battery	176

Home-made meters Pupils with a keen interest in electric circuits can gain profitable understanding and enjoy their success in converting a milliammeter to an ammeter and then to a voltmeter.

But at this stage both understanding and enjoyment may be lost if we do not keep the experiment simple. Avoid calculations of shunt for the ammeter and the series resistance for the voltmeter. Instead, let pupils find the needed adjuncts empirically, just by trial.

For many pupils those construction experiments would be uninteresting, even puzzling—'why put it all together in this muddle when you can buy a good one?' For them, we should offer instead a brief mention of the general story.

Class Expt 127 Making an ammeter *(OPTIONAL BUFFER EXPERIMENT)*

Apparatus

Since only some pupils are likely to try this, the list shows the apparatus needed for *each pair*.

1 galvanometer	item 180
1 d.c. ammeter (0–1 amp)‡	79
1 12-volt battery	176
1 1.5-volt cell	(52B)
2 connecting wires with crocodile clip	(52I)
1 lamp (12 V, 36 W or 24 W)	73 or 72
1 lampholder (S.B.C.)	74
Eureka wire (SWG 28 or thicker)	

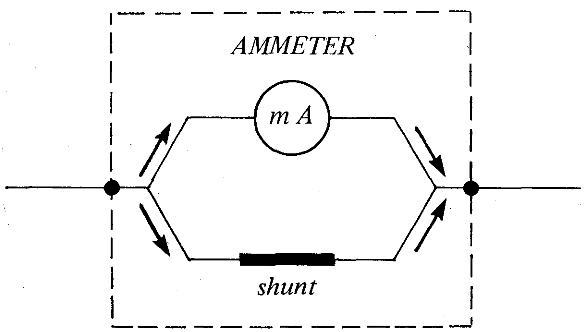
‡ The commercial ammeter enables pupils to adjust their home-made one to read as they wish, by trial instead of by calculation.

Procedure

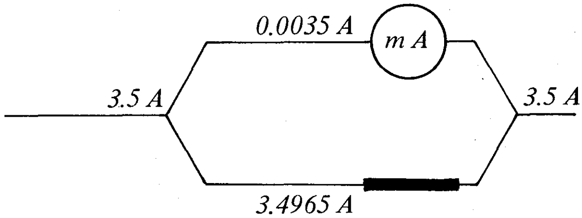
Pupils follow these instructions:

* * * * *

Making an ammeter Your galvanometer is arranged to measure small currents of a few milliamps. Suppose you wish to use it to measure

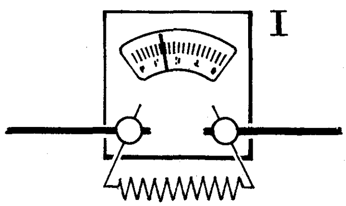


much larger currents, say 3.5 amps at the end of its scale. When the pointer is there, the current through the little coil which moves with the pointer must be the same as ever, say 3.5 milliamps (or whatever your milliammeter is built to measure there). So, if you want to use it for a large current, the rest of that large current (3.5 amps minus 3.5 milliamps, for example) must travel by an alternative route, a loop line in parallel.



shunting a 3.5 milliamp meter to make a 3.5-amp ammeter

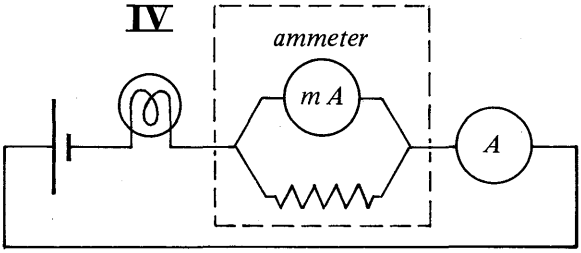
For that loop line or *shunt*, connect a short piece of alloy wire across the terminals of your



galvanometer, as in diagram I. See diagrams II and III for the safe arrangement.*

Start with a very short shunt, straight across from terminal to terminal. Make a very rough test of that by connecting in series a lamp, your shunted galvanometer, a commercial ammeter (for comparison) and one 1.5-volt cell—just for a safe first trial (diagram IV).

IV



Switch on the current just for a moment to see whether the pointer moves much too far or much too little.

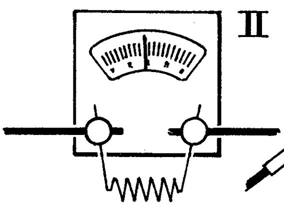
Adjust the length of shunt by trial and error. Shorten or lengthen the shunt until your home-made ammeter seems to read roughly what you want it to read.

Then change the battery in your test circuit to 12 volts instead of 1.5 and adjust the shunt more carefully till you have a good ammeter.

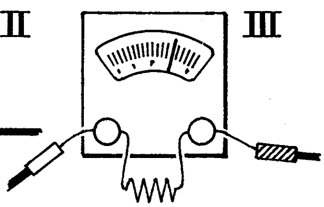
A commercial ammeter is constructed like this. It is a milliammeter with a shunt. Sometimes the basic instrument has several removable shunts to make it an ammeter with a choice of several ranges—as in the case of the demonstration meters in your lab.

* * * * *

* If, when adjusting the shunt, you let the whole big current go through the galvanometer, even momentarily, you might damage the galvanometer badly. Avoid the arrangement of diagram II, which might do that; use the safe arrangement of



II



III

diagram III where there is no danger because the large current always goes through the shunt-wire even when it is off the galvanometer's terminal.

Class Expt 128 Making a voltmeter
(OPTIONAL BUFFER EXPERIMENT)

Apparatus

Since only some pupils are likely to try this, the list shows the apparatus needed for *each pair*.

1 galvanometer	item 180
1 d.c. voltmeter 0–5 volts‡	80 or 179
2 1.5-volt cells	52B
(1 battery to provide 6 volts)	176 or 52B)
Assorted high resistances (The first part will need 1000 ohms; the double range will need 2000 ohms)	

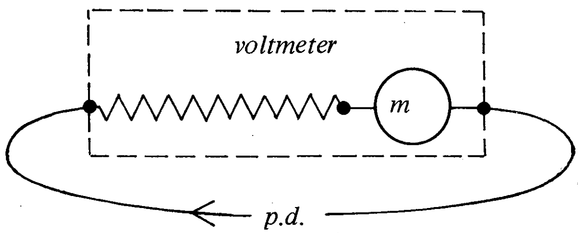
‡ The commercial voltmeter enables pupils to adjust their home-made one to read as they wish, by trial instead of by calculation.

Procedure

Pupils follow these instructions:

* * * * *

The ordinary commercial voltmeter that you use in lab is really a 'trickle meter' that measures the tiny trickle of current that the applied voltage drives through a high resistance inside the voltmeter's case. Your galvanometer *is* a trickle meter. It measures small currents, up to 3.5 milliamps when the pointer is at the end of the scale.



To convert your galvanometer to a voltmeter reading, say, 3.5 volts when the pointer is at the end of the scale, you must add a large resistance in series, as in the diagram.

(If you like making calculations, you could ask: 'what is the total resistance if 3.5 volts applied to the whole instrument drives 3.5 milliamps through it?' Use R = P.D./CURRENT

R = (3.5 volts)/(3.5 milliamps)

= (3.5 volts)/(0.0035 amp) = . . ? . .

Then you know the total resistance needed. The makers of the galvanometer tell us it has resistance 10 ohms. So most of the resistance you have calculated has to be added.)

But you need not calculate. You can discover the right resistance to add by trial. Choose the largest high resistance you are offered. Connect it in series with the galvanometer and connect to a 1.5-volt cell, just for an instant. Does your voltmeter read 1.5, as you wished? If it reads more you do not have enough resistance in it: add more. If it reads too little, try less resistance in it.

When you have adjusted the resistance, try your voltmeter on two 1.5-volt cells in series Also test those with a commercial voltmeter to make sure yours now reads as you wish.

If you like, convert your voltmeter to one with twice that range, 0–7 volts; and try that on a 6-volt battery.

★ ★ ★ ★ ★

Practical example Ask pupils to design the resistance for a practical case: to make an electric arc work.

{A small carbon arc that runs at 4 or 5 amps will give excellent light for casting shadows and other demonstrations in physics. Running at 10 amps, small carbons will be consumed too fast and the arc will wander; and big carbons would give a great big arc. Running at 1 amp, the arc is likely to be unsteady. So, for many purposes a 5-amp arc is best. Across such an arc, running comfortably, there will be a p.d. of 50 to 70 volts. However, the arc is unstable if it is fed by a battery or dynamo of e.m.f. only 70 volts. It must be fed from a 240-volt supply or a 100-volt supply or anything in between, with a ballast resistor in series.}

The ballast resistor for a 5-amp arc taking 50 volts out of 240 volts must waste power (5 amps) × (190 volts), or 950 watts; so no ordinary piece of Eureka or Nichrome will be safe or sufficient to dissipate the heat. However, two 500-watt radiant heaters used in Year 2 can provide just the needed resistance. They are mounted and shielded and could be connected in parallel. Two in parallel would make the arc current about $3\frac{1}{2}$ amps and three in parallel would make it almost 5 amps.

Pupils should calculate the resistance needed, and then see a demonstration of the arc.

Class Expt and Demonstration 129 Making an electric arc work from the mains

AIM: To enable pupils to work out and try a practical case where a resistance has to be calculated, and then used.

Apparatus

16 d.c. ammeters (0–1 amp)	item 79
16 voltmeters (0–15 volt)	179
4 (or more) 12-volt batteries	176
2 demonstration meters	70
1 a.c. dial: 300 volt‡	71/9
1 a.c. dial: 5 amp‡	71/7
3 radiant heaters (as resistors) for the arc	58C
2 *wooden* stands	
2 small carbon rods, or pencil leads	
1 positive lens (+7 D) to make image of arc	

‡ If there is a *d.c. supply* which can provide 5 amps at 100 volts or more, that will make an arc that is easier to run than an a.c. arc. Then the meter dials should be chosen for d.c. and the necessary series resistance may be different. With d.c. the horizontal carbon should be positive.

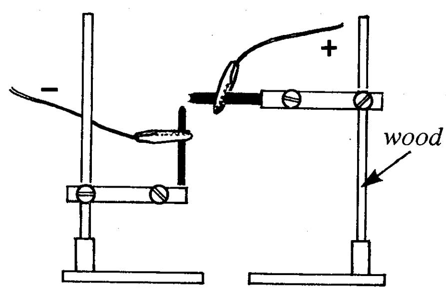
Procedure

A very small arc will run at 4 to 5 amps with a gap of $\frac{1}{2}$ to 1 cm between carbons. There will be about 50 volts across the arc, *but a resistor in series is necessary for stability*. The striking voltage is about 70 volts, but the arc will then run on 50 volts.

The calculation Describe the problem to pupils; the arc needs about 50 volts between the two carbons, but it is to run on 240-volt mains. The rest of that supply voltage must be taken by a resistor in series with the arc. Pupils calculate the resistance needed if the current is to be 5 amps.

Explain that the resistor must dissipate a lot of heat. It must be carefully mounted and protected.

A measurement After the calculation, give



some pupils a group of three 500-watt radiant heaters already connected in parallel (or one 1500-watt element). Ask them to measure the resistance with a battery and voltmeter and ammeter. If their result agrees reasonably with the calculated requirement, proceed with the demonstration.

Demonstration An improvised arc is better than a specially made one.

Set up the arc with carbons held in *wooden* stands, as in the sketch. Use crocodile clips to attach connections to the carbons.

There must be a shield to prevent direct light reaching pupils' eyes.

Show pupils the arc by projecting an image of it on the wall, using a positive lens.

When striking the arc, or adjusting it, always handle *only* the carbon which is connected to the *neutral* terminal of the mains.

Notes

(i) This demonstration needs special care because the arc is running from the mains.
(ii) It is possible to use pencil leads in place of arc carbons. (These will flare dramatically at first since they contain wax.) The pencil leads will get red-hot in use, but they will make a fine little arc, running at 2 to 4 amps.

Fault finding As a buffer option for pupils who are interested, we ask them to imagine that a fault has occurred in an old-fashioned overhead telephone line between two towns. The wires have crossed and made a short-circuit at some unknown point between Town A and Town B. Pupils make measurements of resistance and infer the position of the fault. When they have worked out where the 'fault' must be, they look at the concealed wires and see if they are right.

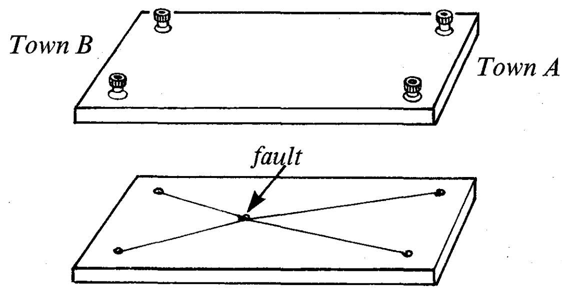
Pupils may ask about the more likely and difficult case of a fault which is an open break inside an insulated cable. We have to tell them that such a break is much harder to locate—though it can be done by capacity measurements.

Class Expt 130 Fault finding *(OPTIONAL)*

Apparatus

8 'fault-finding' boards‡	
8 ammeters (0–1 amp)	item 79
8 voltmeters (0–15 volt)	179
8 rheostats	541/1
4 (or more) 12-volt batteries	176

‡ The boards should be home-made: about 60 cm long, 10 cm wide, with two terminals on top at each end. The ends represent two towns far apart. Telephone wires joining the towns are represented by a pair of $\frac{1}{2}$-metre lengths of alloy wire (e.g. Eureka SWG 28) *underneath the board.* The terminals on top lead to those wires underneath. The resistance of each wire should be at least 2 ohms.



under-side of the board

The fault is a soldered link, joining the wires at some point. (The fault should be somewhere between 0.35 and 0.45 of the way along from one end; then, if pupils use 2 volts, the maximum current in their tests will be less than 1 amp.)

The position of the fault should be concealed with a flap of card or paper, which can be opened for a check.

Procedure

Pupils follow these instructions:

* * * * *

Pretend a pair of overhead telephone wires, the line from Town A to Town B, have developed a fault. At some unknown place on the way one wire has sagged across the other and made a short-circuit which prevents telephone calls.

Act as a telephone engineer and find out where the fault is. You have a battery and ammeter and voltmeter with which you can make tests at the Town A end. Then take them to the Town B end and make tests there.

When you have worked out where the fault must be, uncover the wires and see if you are right.

* * * * *

CHAPTER 13

POWER IN ELECTRIC CIRCUITS

POWER IN A CIRCUIT

Discuss power for the electrical case. We have defined potential difference (in volts) by saying it is a measure of energy-transfer (in joules), for each coulomb passing through the region concerned.

Sketch a simple circuit that includes an ammeter and a lamp. Add a voltmeter across the lamp.

Suppose the ammeter reads 3 amps. The current through the lamp is 3 amps. What does that mean? *That means 3 coulombs pass through the lamp each second.*

Suppose the voltmeter reads 10 volts. What does that mean? *That means each coulomb passing through the lamp delivers 10 joules.*

How fast is energy being delivered to the lamp? Try multiplying:

CURRENT × VOLTAGE = POWER

$$3\,\frac{\text{coulombs}}{\text{seconds}} \times 10\,\frac{\text{joules}}{\text{coulombs}} = 30\,\frac{\text{joules}}{\text{seconds}}$$

or 30 watts

We call a *joule/second* a *watt*, just as a shorthand name. No experiment is needed to show that 100 *watts* is the same as 100 *joules per second*. Watts is merely a name for joules per second. (Comparison with *knots* as *sea-miles per hour* will help.)

Pupils who find this difficult may be offered a very simple analogy:

Suppose a big block of flats is supplied with bread by a number of bakers' men each delivering several loaves. Suppose we know the number of bakers' men passing through the block of flats per day—that is the current in men per day. Suppose we know the amount of bread delivered by each man, in loaves per man—that is like the potential difference. Now we multiply the two together and we have, for example [6 loaves per man] × [10 men per day], which tells us 60 loaves per day delivered at the flats.

(The equivalent story of the country doctor whose wife makes up pills for his patients has an amusing ending. She makes up 6 pills per patient and he sees 10 patients per day, so the total output rate of pills is [6 pills/patient] × [10 patients/day], or 60 pills per day. If by a misunderstanding of arithmetic, we divide instead of multiplying and try [6 pills/patient] divided by [10 patients/day] we obtain a useless number, 0.6, with units that make nonsense, pill·days per square patient. And the example of the baker leads similarly to 0.6 loaf·days per square man.

Moral: work out the units as a check on what you have done.)

We should somehow encourage able pupils to check their work by the units. Remember the dangers of the corresponding game at an earlier stage in arithmetic when men were paid wages to dig ditches of various widths and depths. Pupils were easily confused about handling the data: whether to multiply or divide by a number. Some damage from that confusion will remain now, unless we offer pupils the kindly discipline of keeping track of units. If the data give numbers of pounds per hour, hours per day, men, metres of width, metres of depth, hours per cubic metre excavated, days per working week, and then we ask pupils how many weeks 50 men will take to dig a ditch of a given depth and width and length, they can easily end in confusion, unless they keep the units attached to the numbers. It would almost be worth while to go through such a silly problem, just to show pupils how easy such things are now to work out, especially with the units attached.

Then go back to electrical problems, reminding pupils that changes of *volts* into *joules per coulomb*, and *amps* into *coulombs per second*, and *watts* into *joules per second*, are just dictionary-work, mere changes of name and not changes of science.

Class experiments to give a feeling for power Pupils should make their own measurements of POWER: otherwise 'power' may remain just a name rather than an important physical quantity.

With a lamp run by a battery the energy-changes are *FROM* chemical energy *TO* electrical energy *TO* heat and radiation. Readings of current and voltage give the POWER, *the total rate of transfer* from electrical energy to heat and radiation.

Car batteries must be used, because smooth d.c. is needed for the measurements.*

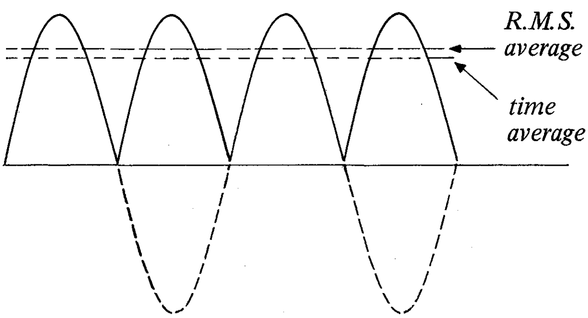
Pupils should also make power measurements for a small electric motor. They should set up and run their own experiment for that—again, so that POWER may become more real.

With a motor, pupils have an opportunity for two estimates: INPUT POWER by multiplying measurements of VOLTAGE and CURRENT; and OUTPUT POWER by multiplying measurements of WEIGHT and SPEED of a load that the motor is raising.

If the motor is just spinning without any load being raised the *useful* output power is zero; then the input power has a disappointing fate: it is all going to fan the air and thus warm it a little!

It is important to give pupils a motor that is robust enough to raise a noticeable load with a reasonable speed. We recommend the larger of the two motor/generators of the Nuffield Energy Conversion Kit (item 9A).*

* With *unsmoothed* rectified a.c. from a simple power supply, the estimate of power obtained by multiplying the readings of a moving coil voltmeter and a moving coil ammeter is likely to be nearly 20% too low. This is because each moving-coil meter measures the simple time-average of the half-cycle humps, and not the root-mean-square average. The r.m.s. values of current and voltage multiplied together give the actual power.



If the peak value of the rectified current is I_0, the r.m.s. average is $I_0(1/\sqrt{2})$, but the simple time-average of that current over each half-cycle is $I_0(2/\pi)$. With a similar treatment for the voltage, the estimate of POWER given by [ammeter reading] × [voltmeter reading] is $8/\pi^2$, or 0.81, times the actual power.

Class Expt 131 Power transferred in a lamp

Apparatus

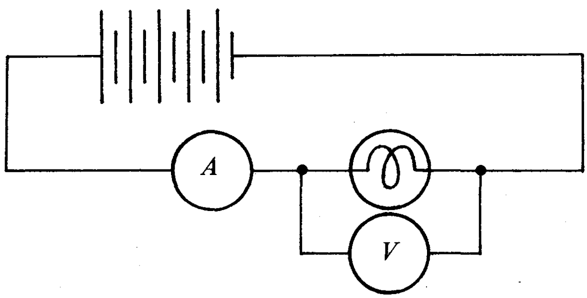
4 (or more) 12-volt batteries	item 176
16 S.B.C. lamps (12-volt, 6 watt)	177
16 lamp holders (S.B.C.) on base	74
16 d.c. ammeters (0–1 amp)	79
16 d.c. voltmeters (0–15 volt)	179

Procedure

Pupils follow these instructions.

* * * * *

Arrange the circuit shown with a voltmeter across the lamp to show the energy-transfer (measured in joules) for each coulomb that passes through the lamp.



* In the first edition, we listed a smaller motor, item 155, just for this one experiment. It had the advantage of costing only about half as much as item 9A, and we suggested that *each pair* of pupils should have one. After further trials, we think it is a little better if each *quartet* of pupils has 9A (making the *total* cost slightly lower). If each *pair* of pupils has 9A that will be much better still.

Needless to say, if the school already has 16 of the smaller motors, (155), they will serve well.

Many other small d.c. motors are available now in model shops, intended for model boats etc, and some of those are suitable. Best of all: the Stuart model, if one can find it.

The ammeter shows how many coulombs of electric charge pass through the lamp during each second.

Record the readings of the meters.

Calculate the energy (in joules) transferred *during each second FROM* electrical energy *TO* heat and radiation.

If you write your record in the following way you will find the calculation clear as well as easy:

Specimen record

Current . . . amps. This means that:
. . . coulombs pass through the lamp in each second

p.d. across motor . . . volts. This means that:
each coulomb transfers . . . joules *FROM* electrical energy *TO* radiation and heat energy in the lamp

Therefore . . . coulombs pass through in one second, each delivering . . . joules

Therefore the power is . . . $\frac{\text{coulombs}}{\text{second}} \times \frac{\text{joules}}{\text{coulomb}}$

. . . $\frac{\text{joules}}{\text{second}}$

. . . watts

* * * * *

Class Expt 132 Power transferred in a motor

Apparatus

4 (or more) 12-volt batteries	item 176
8 or 16 motor/generators‡	9A
or 16 motor generators	155
8 or 16 d.c. ammeters (0–1 amp)	79
8 or 16 d.c. voltmeters (0–5 volt)	80

If possible, pupils should work in pairs, otherwise in quartets.

‡ The motors (item 156) originally suggested are small. Their performance is disappointing. It would be better to use the larger motor/generator (item 9A) of the Energy Conversion kit—either buy 8 more of them or let pupils work in groups of four.

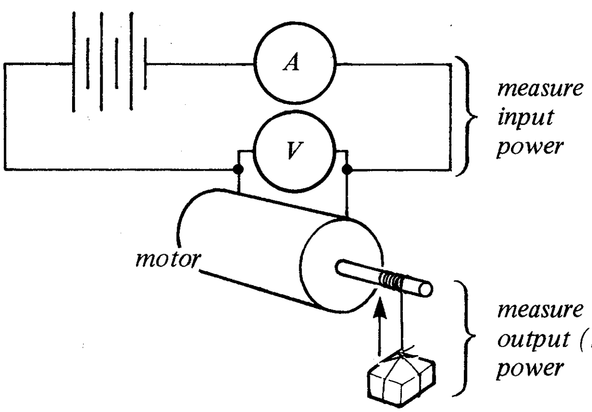
Item 155 needs 4 volts. Item 9A runs on 4 to 6 volts.

Procedure

Pupils follow these instructions.

* * * * *

Measure the electrical power taken by an electric motor. Supply the motor from a 4- or 6-volt battery.



(See optional experiment 133.)

Draw a suitable circuit; then connect it up.

Measure the current the motor takes, and the p.d. across it. Then calculate the INPUT POWER for the motor.

If you write your record in the following way you will find the calculation clear as well as easy:

Specimen record

Current . . . amps. This means that:
. . . coulombs pass through the motor in each second

p.d. across motor . . . volts. This means that:
each coulomb transfers . . . joules *FROM* electrical energy *TO* mechanical energy in the motor

Therefore . . . coulombs pass through in one second, each delivering . . . joules

Therefore the power is . . . $\frac{\text{coulombs}}{\text{second}} \times \frac{\text{joules}}{\text{coulomb}}$

. . . $\frac{\text{joules}}{\text{second}}$

. . . watts

That is all wasted power since your motor is running light. Where does the energy go?

Try loading the motor by applying friction with a card or a gloved finger.

* * * * *

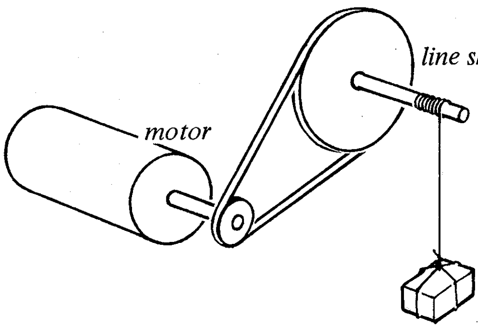
Class Expt 133 Further experiments with a motor *(OPTIONAL)*

The following experiments are suggested for a few pupils who get ahead or have special interests. Since they use the demonstration equipment of the Energy Conversion kit, only a few pupils can work on them at a time.

Apparatus

Each pair will need:

1 12-volt battery	item 176
1 motor/generator	9A
1 *additional* motor/generator, for part *(iii)*	9A
1 d.c. ammeter 0–1 amp	79
1 d.c. voltmeter 0–5 volt	80
1 line shaft	9F
1 driving belt	9M
$\frac{1}{2}$ kilogram	32/1
1 kilogram	32
string	
3 MES bulbs (2.5 V, 0.3 A)	92R
3 MES holders	92T
1 flywheel unit, for part *(iv)*	9E
insulated wire	52Q



Procedure

Pupils who wish to try them follow these instructions.

* * * * *

(i) Make your motor haul up a load Use the same electric circuit as in Expt 132 but arrange your motor with a belt to drive a line shaft which winds a cord to raise various loads ($\frac{1}{2}$ kg, 1 kg . . .; or, for a very small motor 50 grams, 100 grams).

Watch the change of input current as you change the load.

Nuffield model motor If you like, make the model motor of Year 3 again and give it a tiny load to raise. If many members of a class do that they could hold a competition for the best motor for load-raising.

(ii) Measure your motor's efficiency Choose one load (e.g. 1 kg) and estimate the efficiency of your motor; that is

$$\frac{\text{mechanical output POWER}}{\text{electrical input POWER}}$$

multiply that by 100 to express it as a percentage.

To measure the output POWER multiply the WEIGHT of the load (measured in newtons), by the DISTANCE the motor hauls it up *in 1 second.*

Where does the rest of the input power go?

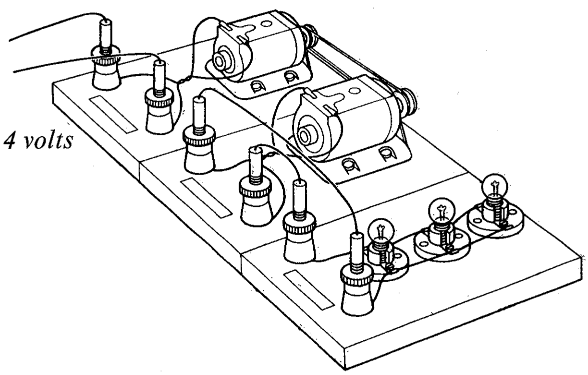
A load to be raised makes a demand on a motor. An electric motor can adjust to such demands over a wide range of loads. What is the useful OUTPUT POWER of your motor when it is asked to raise *no load at all?* What is its OUTPUT POWER when it is asked to raise such a *huge load*, that it stalls?

Find, by trial and error, the load that seems to make your motor give its *maximum* OUTPUT POWER.

Maximum power Make a rough estimate of that maximum OUTPUT POWER and compare it with the INPUT POWER for the same load.

Animals and human beings are adjustable like that motor: they can adjust their output FORCE over a wide range, and their OUTPUT POWER behaves rather like that of an electric motor (though for a different reason). Think about your own OUTPUT POWER in raising various loads with a rope and single pulley. Can you prove, even without trying it, that there must be some load for which you can put out *maximum* power?

(iii) Make your motor drive a dynamo which lights 1, 2 or 3 small lamps in parallel.



Measure the INPUT POWER for the motor as before.

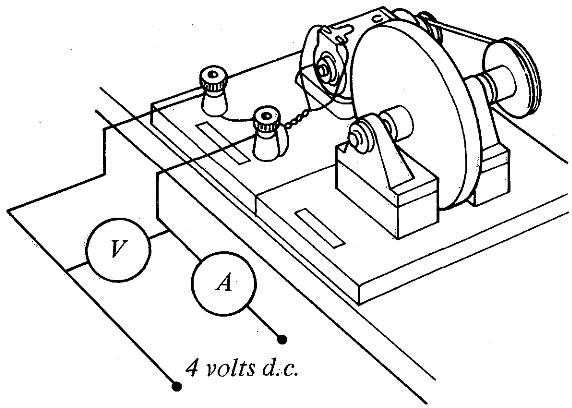
Then move the ammeter and voltmeter to measure the OUTPUT POWER from the generator to the lamps—or borrow another pair of meters.

Watch the current and the motor's speed as you turn on more lamps—you are running a miniature power station with your motor taking the place of a steam engine.

Can you estimate the efficiency of the motor-generator combination? It is:

$$\frac{\text{output POWER of generator}}{\text{input POWER for motor}} \times 100\%$$

(iv) Let your motor drive a massive flywheel Watch the power input to the motor while the flywheel is accelerating; and again when the flywheel is spinning at constant speed.



When the flywheel has reached constant speed, where is the energy going?

How can you get the energy that is now stored in the spinning flywheel back into electrical form? Try that.

* * * * *

Pupils are likely to be very disappointed with the estimated efficiency of their motor. To restore their faith somewhat, give all the class a demonstration with a commercial motor, the fractional horse-power motor.

Demonstration 134 Power of a fractional horse-power motor

Apparatus

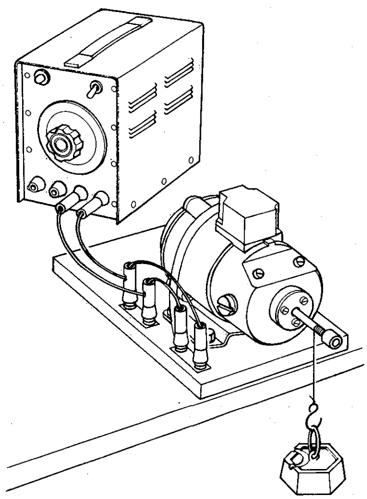
1 fractional horse-power motor	item 150
1 L.T. variable voltage supply	59
2 demonstration meters	70
1 d.c. dial: 5 amps	71/2
1 d.c. dial: 15 volts	71/10
1 switch	224
1 kilogram	32
1 metre rule	501

Procedure

The motor is already mounted on a board. Clamp it at least 1.5 metres above ground level.

Attach string to the spindle. (The simplest method is to drill a small hole through the spindle. A $\frac{1}{2}$-cm piece of rubber tubing pushed over the end will prevent the string coming off the spindle.)

Set up the circuit as shown, with the field coil and armature in parallel. Then install meters.



Adjust the supply to about 4–5 volts. Attach a kilogram to the lower end of the string. Press the switch. The string winds up on the spindle and the lead is raised. It will rise a metre in 4 or 5 seconds.

It is important to choose a voltage such that the load rises without marked acceleration. If smaller loads are used the supply voltage will have to be reduced.

Alternative view We might tell pupils that the potential difference as a measure of energy transfer in joules per coulomb is the same thing as a *current-rate* of supplying power, in watts per amp. Actually, this is a legal definition; and some pupils find it conceptually easier because both the terms [rate-of-delivery-of-energy in *joules per second*] and [rate-of-flow-of-charge in *coulombs per second*] are 'continuous' and feel more familiar. To illustrate that, we point out that a 100-watt bulb that is taking a $\frac{1}{2}$-amp current is running at a power/current rate of 200 *watts per amp.* Therefore, the potential difference across the bulb must be 200 *volts.*

FORMULAE FOR POWER

Pupils should now express the rule for power in the form:

power $= V.I$

Then they should use Ohm's Law in the form:

P.D./CURRENT = a constant called RESISTANCE,

$$V/I = R$$

and arrive at the statement:

POWER $= RI^2 = V^2/R$ as well as the form $V.I$

We should, of course, tell pupils that these 'formulae' will appear on the front of their examination paper, so that there is no point in memorising them.

Model power line This experiment was suggested in Year 3—a very important one for understanding power distribution. The point of the experiment is that pupils should see for themselves (rather than just be shown in a demonstration) the importance of using high voltages for long-distance power lines. We hope that it will be given plenty of time—*now* if not in Year 3—and further time for the a.c. version in Year 5. It is best to keep the d.c. case well clear of the a.c. version.

Pupils can now repeat the d.c. power line with voltmeters and ammeters to make measurements. Yet the importance of the qualitative experiment lies not in the measurement of power but in the qualitative change from a highly inefficient line to a highly efficient one. Teachers who have not tried this experiment will be amused themselves by the impressive demonstration.

Class Expt 135a
d.c. Model power line

Apparatus

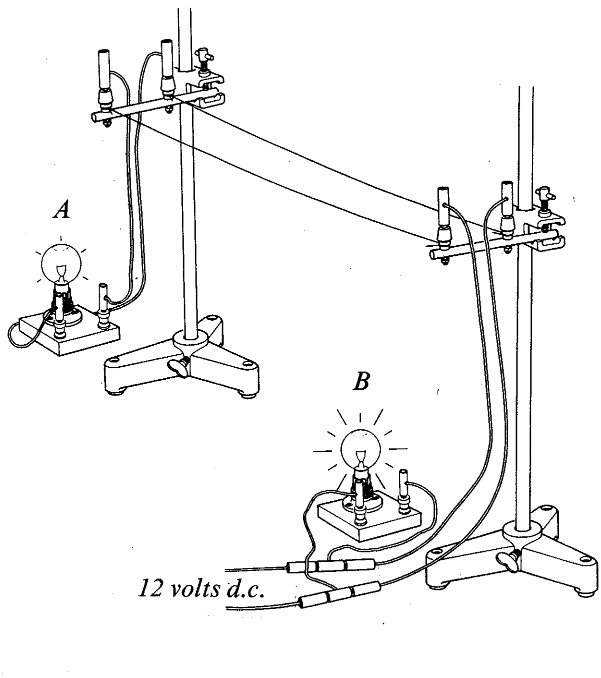
16 power line terminal rods	item 99
16 retort stands	503–504
16 bosses	505
16 lamp holders (S.B.C.) on base	74
16 S.B.C. lamps (12-volt, 24-watt)	72
16 4-$1\frac{1}{4}$ metre lengths bare Eureka wire (SWG 28)	98
4 (or more) 12-volt batteries or equivalent	176
8 ammeters (0–5 amp)	178

(4 mm plugs on the connecting wires are a help; they make the setting-up simple and quick for pupils. Yet they are a luxury, not essential for this experiment, because the power line wires can be anchored permanently by the screws under the terminals on the dowels, while ordinary connecting wires are inserted in the terminals for the experiment.)

Preparation

The power lines In this model, the power lines of Eureka (constantan) SWG 28, are held by terminals on wooden dowels. Each dowel is horizontal, held in a boss on a retort stand, about 30 cm above the bench. The stands are placed about $1\frac{1}{4}$ metres apart, so that the power lines are almost taut.

It saves considerable time if the power-line wires are attached to the dowels beforehand. After the experiment, the pair of dowels with the wires attached can be rolled up into a loose bundle for storage. However, if there is room to hang the assemblies vertically from pegs on a wall, there is less danger of tangling.



The pylons If the stands can be prepared beforehand, two stands for each group of pupils, with a boss fixed on each stand about 30 cm above the bench, pupils will get to the real work much more quickly. This is an experiment where beginners may take a lot of time over the mechanical setting-up without relevant profit. If it is not feasible to set up the stands beforehand (and perhaps the power lines too), there should be a specimen assembly already set up on some side table; that will help pupils to see what is needed and will save time and confusion.

The 'power station' Each group needs a supply that can deliver 4 or 5 amps at 12 volts. A 12-volt car battery will do well as the basic supply, and one battery can feed several groups. (Although an a.c. supply would do equally well for this qualitative experiment, d.c. will be essential for the later experiment with measurements; so it would be better to start with d.c. now.)

Procedure

Pupils follow these instructions.

* * * * *

Take a battery to represent a power station connected to one end of a power line which feeds a village far away at the other end.

Set up your power line with its thin wires stretched between two tall stands. The wires are made of high-resistance metal to imitate the resistance of a very long, real power line.

Connect a lamp A at the far end of your power line from the power station. That lamp represents the village.

Connect the 12-volt supply direct to the terminals at the near end of the power line.

Also install a lamp B connected straight to the 12-volt supply which represents the power station. That lamp is the power-station engineer's reading lamp.

Run your electric power grid and see how well it supplies the lamps. Why does the village lamp suffer?

If you like, install an extra lamp, C, at the village in parallel with lamp A. How well does the power system supply those two?

* * * * *

The lamp at the village will only just glow, in contrast with the power engineer's lamp at full brightness.

High voltage power line Before giving any explanation, proceed to a similar experiment with high voltage, 240 volts instead of 12 volts. This needs to be a demonstration.

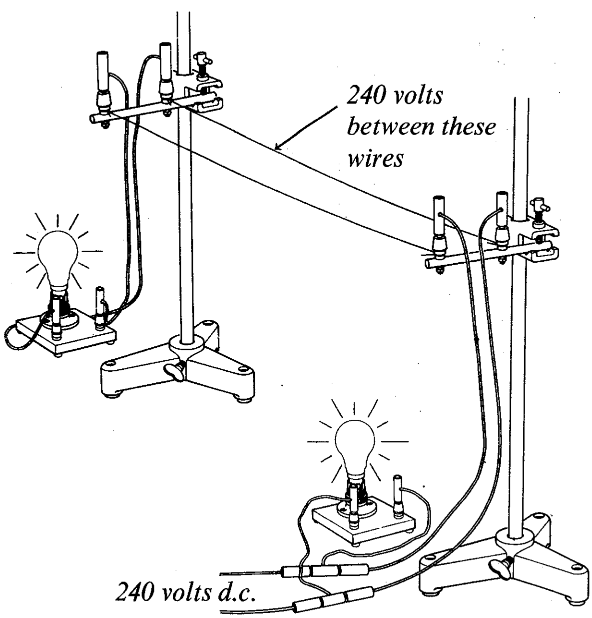
Demonstration 135b •
d.c. Model power line at high voltage

Pupils should do the low-voltage experiment themselves, without being warned what to expect. But this important sequel must be done by the teacher because it uses 240 volts between the two wires of the power line.

Apparatus

Use one of the power-line assemblies already set up by pupils, but change the power station and lamps appropriately. The following additional apparatus will be needed:

1 H.T. power supply (failing that, use a.c. mains)	item 15
2 lamp holders (B.C.) on base	162
2 240-volt lamps 15 watt	70



Procedure

Use one of the power-line assemblies that pupils have been using.

Replace the low-voltage lamps by 240-volt 15-watt lamps and the 12-volt 'power station' by the H.T. power supply giving 240 volts d.c.

Pupils will see how much more efficient in power transmission the high-voltage line can be.

If pupils ask just how it is that the high-voltage line can do so well, insert an ammeter in the connection from the power station to the power line and let pupils see the small current. Then ask pupils to go back to a low-voltage assembly and insert an ammeter between the battery and the power line. There the current is much greater for the same power at the village, and the wires of the power line are heated with greater waste of power.

Then pupils calculate the power used by the village and the power supplied by the power station, and thence a measure of the efficiency,

$$\frac{\text{power output at village}}{\text{power input at power station}}$$

The teacher should return to his demonstration power line with the higher voltage and make similar measurements with voltmeter and ammeter. (Reminder: there will be 240 volts between the two power lines.)

Measurements By connecting a voltmeter across various parts of the power-line demonstration, pupils can estimate the power supplied by the 'power station' and the power used by the 'village'. A fast group who understand voltmeters should make these measurements; but this should not be laboured with other groups who would find it hard.

Class Expt and Demonstration 136 Measurement of power in model power line *(OPTIONAL)*

Apparatus

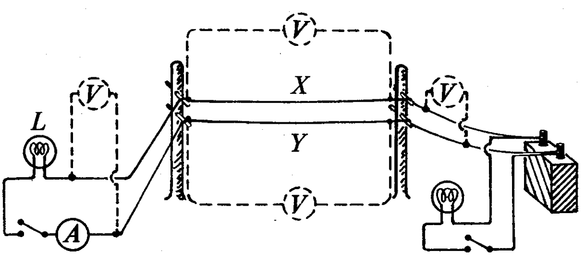
The same apparatus as for Expt 135a and b together with:

8 ammeters (0–5 amp)	item 178
8 voltmeters (0–15 volt)	179
2 demonstration meters	70
1 d.c. dial (300-volt)	71/11
1 d.c. dial (0.1 amp or 1 amp)	71/12 or 71/1

Procedure

Pupils return to their own power lines. They connect an ammeter in the supply line.

They first connect the voltmeter across the 'village lamp', to measure the energy-transfer in joules per coulomb. Then they connect it across the supply at the power station to measure the energy transfer there. Also, optional, across X, Y.



Class Expt and Demonstration 135X a.c. Power line *(OPTIONAL NOW)*

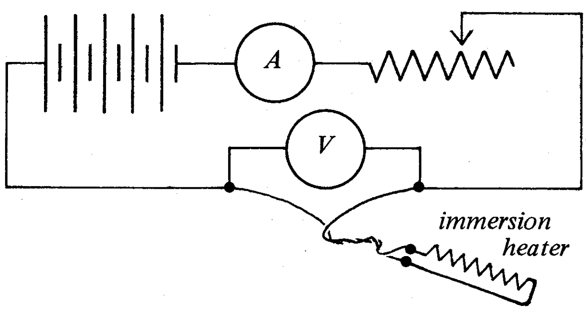
This is probably best postponed to Year 5. Teachers who wish to offer it now will find details in *Teachers' Guide 5*.

Class Expt 137 Electrical measurement of the specific heat capacity of aluminium

(OPTIONAL EXPERIMENT; an alternative form of the measurement in Chapter 9 which did not use a voltmeter but made a comparison with water instead)

Apparatus

4 (or more) 12-volt batteries‡	item 176
8 immersion heaters	75
8 aluminium blocks	77
8 ammeters (0–5 amp)	178
8 voltmeters (0–15 volt)	179
8 thermometers	542
8 stopwatches or stopclocks	507
8 rheostats (10–15 ohms)	541/1
1 kitchen weighing scale	206

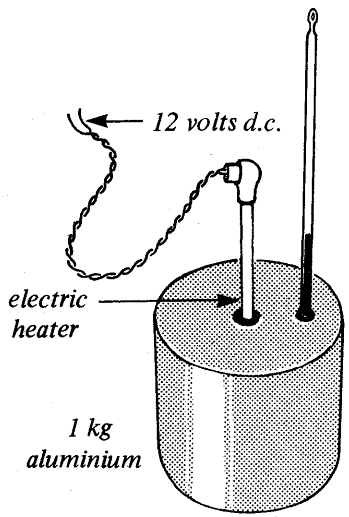


‡ Moving-coil meters should be used for this experiment, with d.c. from a 12-volt battery or a *well-smoothed* power supply. (The use of moving-coil instruments on *unsmoothed* d.c. can lead to an error of

nearly 20% in the result. The d.c. meters read plain time-averaged values. For *unsmoothed, rectified* a.c. each such average is (PEAK VALUE) $\times (2/\pi)$. But the heating is determined by r.m.s. values, each of them (PEAK VALUE) $\times (1/\sqrt{2})$. Then the product of the meter readings of current and voltage will be $8/\pi^2$ (about 0.81 times the proper product for power-transfer).

Procedure

The heater is to be inserted in the central hole of the aluminium block. The thermometer goes in the other hole. Some paraffin oil inserted in the thermometer hole will ensure good thermal contact with the block.



It is better not to use oil in the hole for the heater as there is a danger of 'cracking' any oil which is left on the heater when it is removed from the block.

Pupils follow these directions:

* * * * *

Connect up the circuit as in the diagram. The heater is designed to run on a 12-volt supply and deliver 40 to 60 watts. Keep it switched off, until you are ready.

Switch on, and adjust your rheostat quickly to make the current 3 or 4 amps. Switch off again as soon as you can.

Before switching on for the main experimental run, wait for 5 minutes to let the block reach a uniform temperature.

Take the temperature, and record it. Switch on and start the clock.

Keep the heater running for a measured time, say 5 minutes.

Switch off. Watch the thermometer and record the *maximum* temperature reached.

Weigh the block to find its mass (measured in kilograms).

Calculate the electrical energy supplied. That will be measured in:
volts $\times$ *amps* $\times$ *seconds* (for the time the current ran) or (*joules*/*coulomb*) $\times$ (*coulombs*/*second*) $\times$ (*seconds*), that is *joules*.

To calculate the specific heat capacity, divide that energy by the mass of aluminium and by the *maximum* temperature-rise.

That will tell you the energy (measured in joules) needed for each kilogram for each degree rise of temperature. That is called the specific heat capacity of aluminium.

Specific heat capacity of water If you like, repeat this measurement with a saucepan of water instead of the aluminium block. That will give you the specific heat capacity of water—the energy (in joules) needed for each kilogram of water for each degree rise of temperature. From Chapter 9, you might expect about 4200 but your measurement is unlikely to agree closely. Why?

Then you can calculate the comparison number, c–n, for aluminium by dividing specific heat capacity of aluminium by specific heat capacity of water.

* * * * *

Note: The measurement with the block of aluminium only gives a rough estimate. A slightly more accurate one can be obtained by reading the temperature every half minute during the heating, plotting a temperature-time graph and using the *slope* of its straight part. But that will confuse some pupils and may build up a sense of pressure to get the right result—which hardly seems justified for the specific heat capacity of aluminium at room temperature.

For greater accuracy, the aluminium blocks could be lagged with polystyrene; but again this experiment is intended to illustrate a concept rather than yield an accurate result.

CHAPTER 14

ELECTRONS

Electron streams; Millikan's experiment

ELECTRONS

Introduce electrons by a class experiment with a diode tube. This follows directly on Ohm's-Law experiments with currents in wires, etc. So we do not have to begin with any special stories about discharge tubes; we do not have to use dangerously high voltages; we simply let pupils see a new, strange behaviour, with delight.*

Once pupils have learnt about the negative stream from a hot filament, we do have to bring in other knowledge; but they will feel they have made a start on electrons.

THE DIODE DEMONSTRATION

There are two good ways of introducing the diode:

(1) We offer it as one more device, like a sample semi-conductor, for which we make measurements of p.d. and current, first with the filament cold and then with a heating current supplied. We give no description or explanation except that, when pupils ask, we tell them what there is in the diode, mentioning the vacuum and the hot filament.

Or, (2) We tell pupils that we believe that metals contain some very mobile carriers (which *they* will tell *us* are electrons) and we ask them to picture those carriers in rapid random motion, somewhat like molecules of a gas. (In fact, the statistics of electron motion in a metal are not the same as those for gas molecules in a gas and we might mislead pupils by this description.)

We try to picture what happens if we make the metal hotter and hotter. If this makes the carriers in the metal move more and more energetically, as it would with gas molecules, we might expect to see some of the carriers escaping from the surface of the very hot metal—and then they might be driven across to another place, their motion constituting a current.

In the latter treatment (2), we suggest that we should heat up the filament of the diode and see if any carriers evaporate.

In treatment (1) we do not make any such suggestion, but just show the diode's behaviour first with cold filament and find that for whatever voltages we apply there is no current. Then we try the same thing with a hot filament, still with a vacuum intervening between cathode and plate.

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* It would be much better teaching to let pupils have diodes for a class experiment. Unfortunately the march of progress has put hot-cathode diodes out of date; and the only good form we can offer is a Teltron demonstration diode. That at least has the advantage of being so large and simple that its structure is clear. Small diodes are doubtless available on the secondhand market but it is not easy for pupils to see their structure, and they are becoming obsolete; so we do not suggest a class experiment with them. Solid-state diodes are of course available but they do not provide the introduction to an electron gun which we need now for the fine beam tube.

That is why we suggest a demonstration with the Teltron diode.

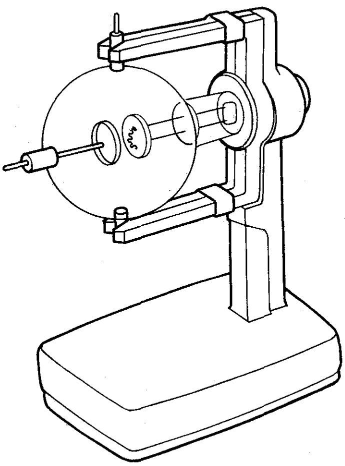
Demonstration 138a The diode as an electron gun

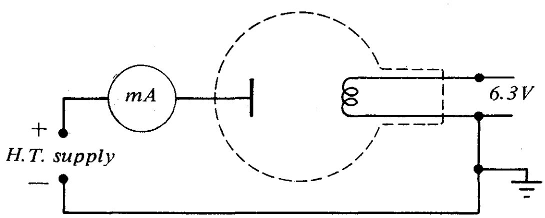
(Since hot-cathode diodes are now practically obsolete, we use the Teltron demonstration diode as an introduction to electron guns.)

The diode could have been shown as one more example of unusual behaviour in Chapter 12 but since it needs an auxiliary circuit to heat the filament it seemed too complicated to be placed among the semi-conductors. Now it is essential as an introduction to the fine beam tube. So the purpose of this experiment is not to study the characteristics of diodes but to show the action of an electron gun.

Apparatus

1 hot filament diode tube, Teltron	item 135
1 stand for diode	140
1 H.T. power supply	15
1 demonstration meter	70
1 2.5–0–2.5 mA dial	71/4





Procedure

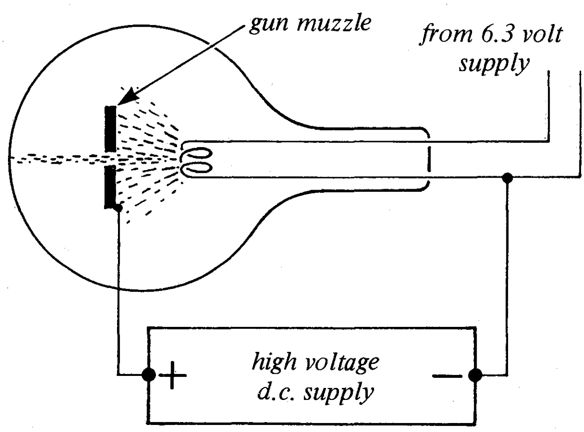
Set up the diode in the stand and apply 6.3 volts to the filament.

Connect the plate in the tube through the demonstration milliammeter to the H.T. power supply. Earth the other terminal of the supply and connect it to one of the filament terminals. The supply should keep the plate at 400 volts either positive or negative relative to the filament.

Show the action of the tube first with the filament cold, then with the filament hot.

Whatever the p.d. across the tube no current flows as long as the filament is not glowing. When the filament is hot, a current flows if the plate is positive. No charge flows if the plate is negative.

Ask pupils to imagine a hole drilled in the plate—then they have an electron gun.



THE IDEA OF AN ELECTRON GUN

Note: With no p.d. across a diode, a small current may be observed. This is *not* due to the energy with which electrons are emitted from the filament—that effect is many times smaller.

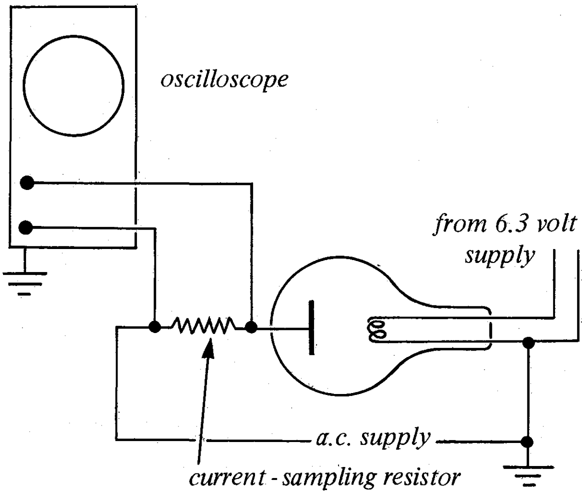
The current flows because the mid point of the filament is used for the filament-plate voltage; then even when that voltage is 0 there is a small accelerating voltage between one *end* of the filament and the plate.

Demonstration 138b The diode as a rectifier shown on the C.R.O.

(Pupils should see a solid-state diode acting as a rectifier; but since the hot-cathode diode is being shown now its action as a valve should also be exhibited.)

Apparatus

1 hot filament diode tube, Teltron	item 135
1 stand for diode	140
1 H.T. power supply (for filament, 6.3V)	15
1 demonstration meter	70
1 2.5–0–2.5 mA dial	71/4
1 demonstration oscilloscope	64
1 transformer	27
or variable voltage supply	59
1 resistor, 1500 ohms ($\frac{1}{2}$ watt)	132I



Procedure

Connect in series a 12- or 24-volt a.c. supply, 1500 ohms as a current sampling resistor and the Teltron diode.

Take leads from the sampling resistor to vertical input terminals of the oscilloscope. It is best to make sure that the earth side (if any) of the a.c. supply is connected directly to one end of the load resistor; and that end connected to the earth terminal of the oscilloscope.

First show the wave-form of the a.c. without rectification. (Remove the diode for that, or bridge it with a wire.)

Ask pupils to *guess* what the pattern will look like with the diode in action. Ask each to record his or her guess on paper.

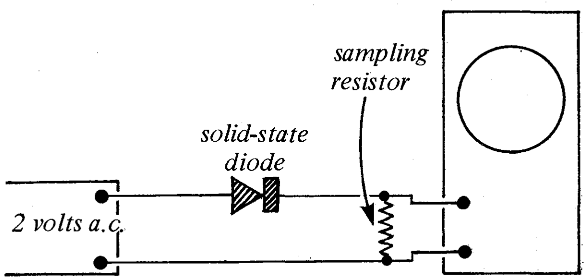
Then show the half-wave rectified pattern.

Demonstration 138c Solid-state diode as a rectifier

Since small silicon diodes are available and cheap (less than 5p) pupils should work with one as a class experiment. Only if class oscilloscopes are not available should this demonstration be given instead.

Apparatus

1 silicon solid-state diode, e.g. 1N4001*	item 243 or 52G
1 demonstration oscilloscope	64
1 transformer	27
1 resistor, 1500 ohms ($\frac{1}{2}$ watt)	132I



Procedure

Connect in series a 2-volt a.c. supply, 1500 ohms as a load and the silicon diode.

Take leads from the load resistor to the vertical input terminals of the oscilloscope.

First show the wave-form of the a.c. without rectification. (Remove the diode for that, or bridge it with a wire.)

If pupils have not seen the Teltron demonstration and tried to guess the rectified wave form ask them now to guess what the pattern will look like with the diode in action. Ask each to record his or her guess on paper.

Then show the half-wave rectified pattern.

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* New Nuffield item.

Class Expt 138d Solid-state diode as a rectifier

Apparatus

8 silicon solid-state diodes, e.g. 1N4001 item 243 or 52G	
8 transformers	27
8 class oscilloscopes	158
8 1500 ohms ($\frac{1}{2}$-watt) resistors	132I

Procedure

Pupils follow these instructions.

* * * * *

Connect the diode to the transformer and the sampling resistor 1500 ohms as in the diagram (Expt 138c).

Take leads from the ends of the resistor to the vertical input terminals of your oscilloscope.

Set your oscilloscope on time-base range 2, with the input switch to d.c. and the gain set between 0.1 and 0.5 div/volt.

Look at the wave-form of the a.c. supply without the diode (just bridge across it with a wire for the moment).

Then guess what the wave-form will look like with the diode in action as a valve.

Then look at the wave-form with the diode in action. If the pattern is upside down from what you expect, reverse the diode.

If you like, you could carry this one a stage further and make a 'full-wave rectifier' arrangement with four diodes.

* * * * *

Class Expt 138e Full wave rectifier with solid-state diodes *(OPTIONAL)*

Apparatus

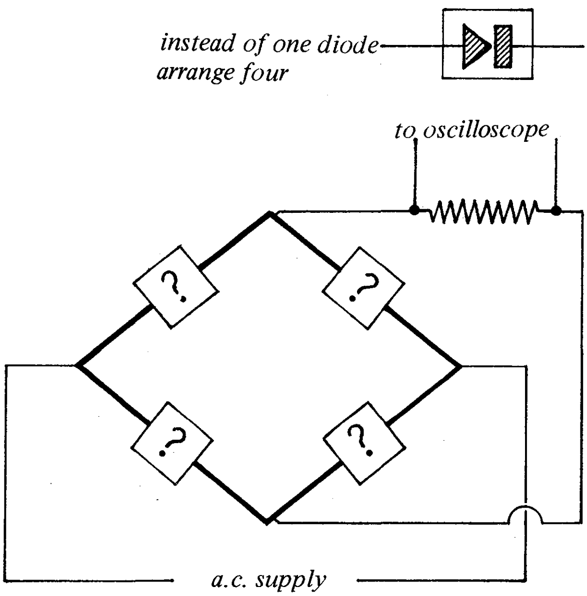
Since only some pupils are likely to try this, the list shows the apparatus needed for each *pair* of pupils.

4 silicon solid-state diodes, e.g. 1N4001	item 243 or 52G
1 transformer	27
1 class oscilloscope	158
1 1500 ohm resistor ($\frac{1}{2}$ watt)	132I

Procedure

Pupils follow these instructions

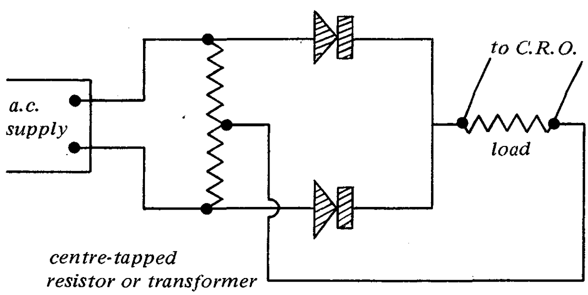
* * * * *



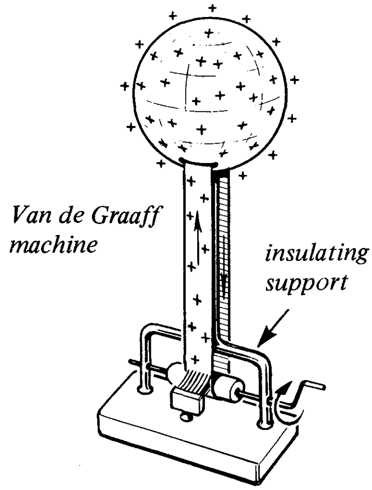
Arrange a 'bridge' circuit as in the diagram. Think about the way to arrange the four diodes so that in the course of a cycle of the a.c. supply current will go through in *each* half cycle and make humps in the same direction. The sketch does not show you which way each diode must point. You need to decide that.

* * * * *

The alternative form with a centre-tapped transformer or resistor is no easier for beginners.



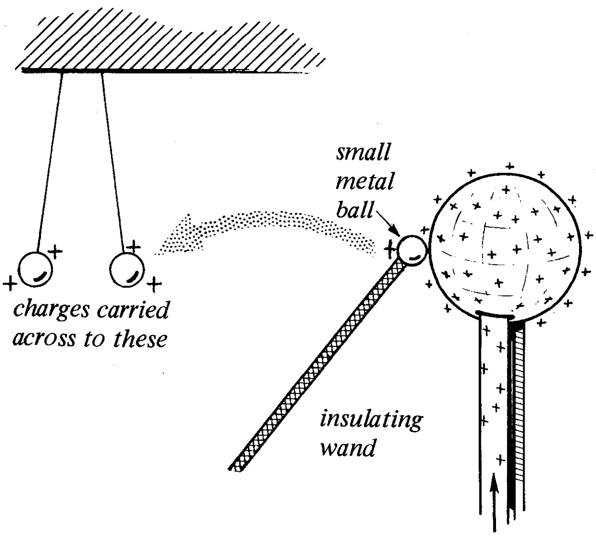
Some pupils may have missed the treatment of electrostatic charges in Year 3. There, we gave experiments that used current sources and electrostatic generators and produced the same effects. So we offer here a small group of demonstrations all numbered 139 in case they are needed. Since time is short and pupils should meet Millikan's experiment before this year ends, we urge teachers not to give time to these catching-up experiments with pupils who met them before; but only to use them for emergency treatment if pupils missed the work completely.



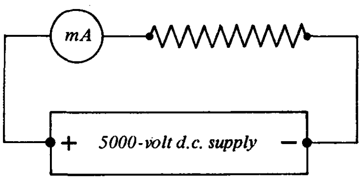
Demonstration 139 Electrostatics for catching up

For apparatus and procedure, consult *Teachers' Guide* for Year 3.

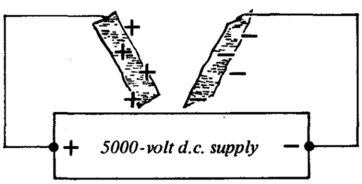
Year 4 Expt	*Year 3 page*	*Teachers' Guide 3 Expt Number*
139a	231	118 a, b, c
	232	118 h*(i)*
	232	obtain opposite charge by induction
	232	118 h*(i)*
139b	231	118 f
		118 e
139c	235	119
		(+ and − point charges)
		(+ and − parallel plates)



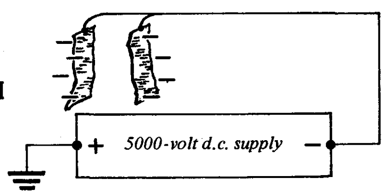
I

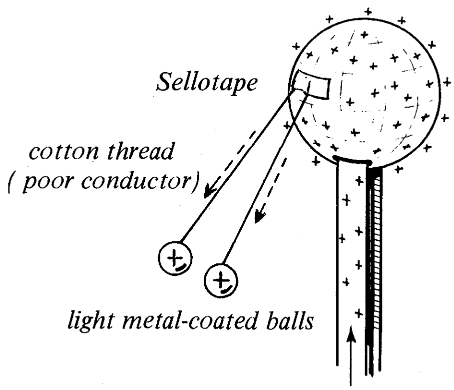


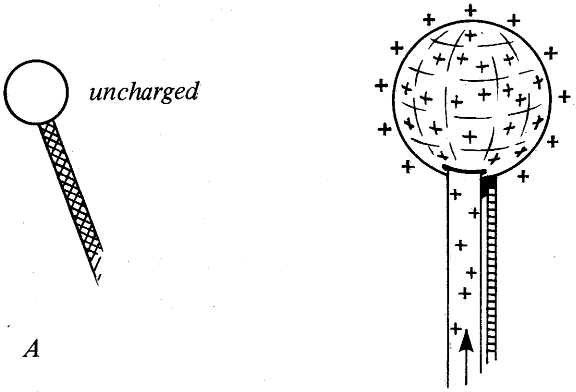
II



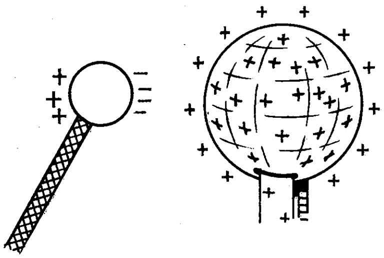
III



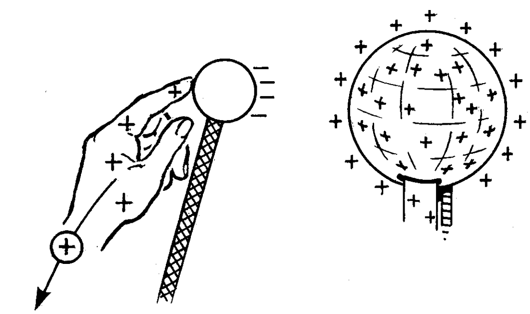




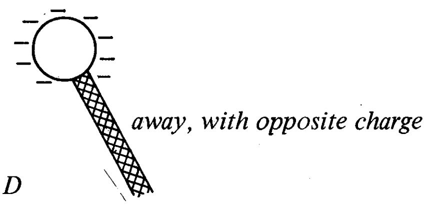
A



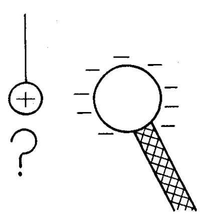
B



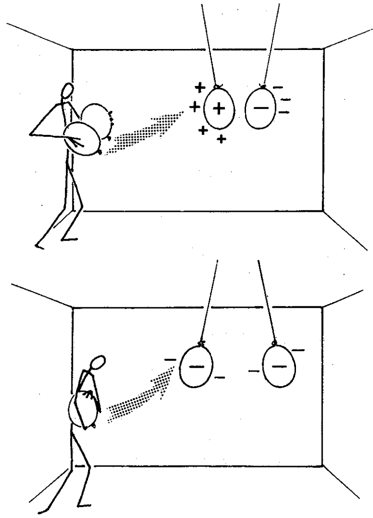
C touch with finger momentarily

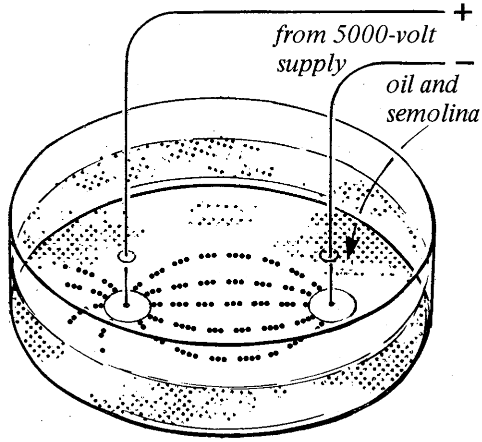


D

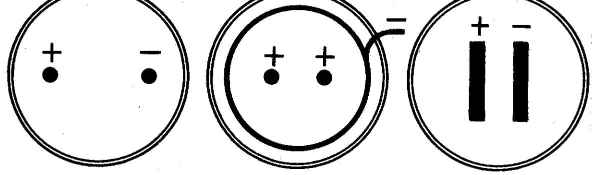


E

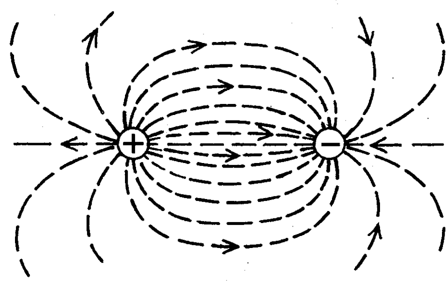


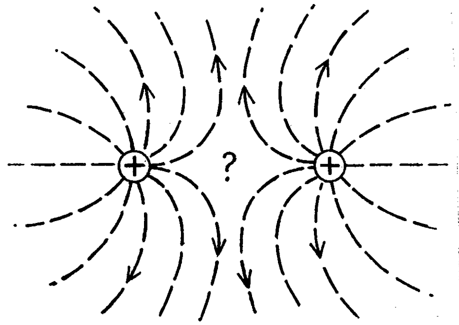


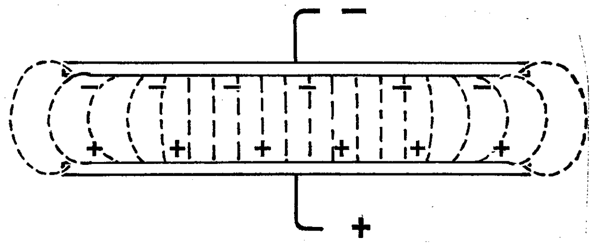
patterns made by grains of semolina



A B C







A VISIBLE STREAM OF ELECTRONS

At this point show the Teltron (or Leybold) fine beam tube again. (Some Nuffield teachers feel that it spoils the fun to bring this tube out year after year; but others regard it as a very important general piece of apparatus which should come out just as often as a voltmeter.) This tube should not be solely an object for wonder in this electronic age; it should be an essential tool for further learning; and it *should* come out again now.

Show the beam first with a low voltage on the horizontal gun so that the beam loses all its energy in a short distance in the thin helium in the tube; then with bigger gun voltage so that the beam hits the wall of the tube.

Apply a deflecting *electric* field to the stream. Explain that the gun itself has an accelerating voltage in it; but the electric field that we now apply is a transverse field that pulls the electrons sideways, giving them some sideways momentum in addition to the forward momentum provided by the gun.

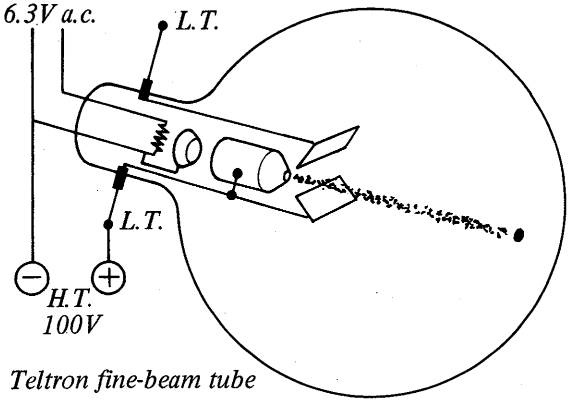
Try a slowly alternating voltage on the deflecting plates and also rapidly alternating voltages.

Demonstration 140a Fine-beam tube

The Teltron tube meets our suggestions better than designs previously recommended; so the instructions below refer to the Teltron tube; but if the school already has a tube of another make that should certainly be used.

Apparatus

1 fine-beam tube and base	items 61, 62
1 H.T. power supply	15
1 L.T. power supply	59

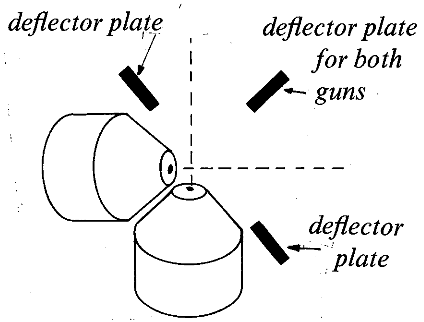


Teltron fine-beam tube

Tube connections

Heaters The sockets at the back of the base cap are for the cathode heaters. Connect them to a 6.3 volt (a.c.) supply. The socket marked – must also be connected to the *negative* terminal of the H.T. supply for gun voltage. The two-way switch on the cap puts one gun or the other in action.

Gun voltage One of the side terminals on the tube leads inside the tube to the muzzles of both guns. Connect that to the *positive* of the H.T. power supply, starting with 100 V d.c.



dual gun assembly
(switch for guns is in base cap)

The deflecting field Just outside each gun muzzle there is a pair of plates for deflecting the beam by an electric field.

One plate of each pair is attached directly to the gun muzzle which supports it. The other plate of each pair is connected inside the tube to the second side terminal on the tube.

Connect that side terminal to the *positive* of a variable L.T. d.c. supply. To complete the connections to the deflection plates, connect the *negative* of the L.T. supply to the gun muzzle (the + of the H.T. supply).

A small p.d. of 1 or 2 volts between these plates will usually make the beam focus more sharply.

When the beam is to be deflected visibly by an electric field, increase that p.d. to 20 or 30 volts.

Procedure

For pupils to 'see' an electron stream, use the gun which fires straight along the axis of the tube, to the fluorescent screen.

Heat the cathode, then turn on the H.T. gun voltage and let pupils look at the tube closely in a half dark room. For many, this will be their first glimpse of a 'visible electron stream' and they need time to enjoy looking; then give an explanation.

If the beam fails to make a clear spot on the screen try two cures:
(i) vary the small p.d. applied to the deflecting plates.
(ii) clean accumulated charges off the screen by sweeping the beam up and down it and across it.

Explanation *(as in Pupils' Text 3)*

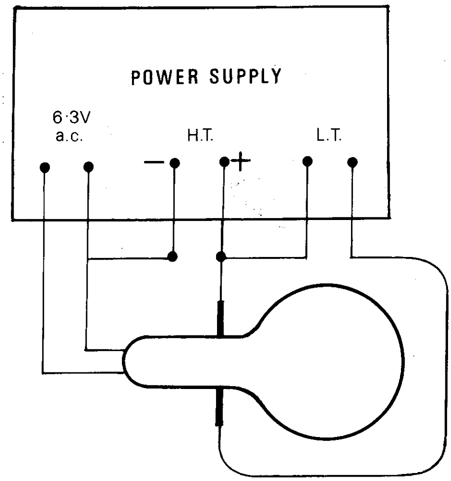
* * * * *

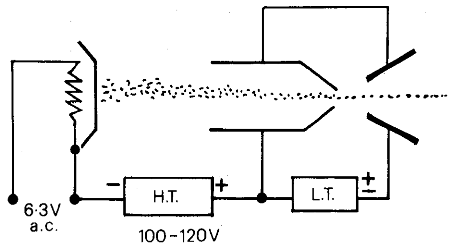
At one end of the tube there is a little cone-shaped 'gun'. In that gun a starting plate is heated by a tiny electric grill.

The plate has a special surface that lets electrons loose rather easily. Electrons boil off that plate. They are speeded up in the gun by a large voltage between that starting plate ('cathode') and the gun muzzle ('anode').

Electrons come out at high speed through a tiny hole in the cone-shaped muzzle.

We can calculate their speed from some measurements. It is more than 5 000 000 metres per second (20 million kilometres per hour or 12 million miles per hour!)





The electrons continue at that constant speed to the end of the tube and make a bright spot where they crash against the mineral screen.

This is like an oscilloscope tube, but naked so that you can see inside. The tube in a cathode ray oscilloscope or a TV picture tube has an electron gun just like that: but here the stream from the gun muzzle is made visible. This glass globe has been pumped out to a very good vacuum to remove air, which would soon slow electrons down by collisions. But then a *very little* helium gas is let in, because the helium atoms give out a green glow when hit by electrons.*

So you can see the path of the electrons made visible as a thin line of glow.

Look at that carefully. You are seeing the path of electrons flying through thin helium, almost a vacuum, all by themselves, with no wires there.

* * * * *

* A similar tube of another make has a thin atmosphere of hydrogen, which makes a faint blue glow, instead of the green glow of helium.

Demonstration 140b Fine-beam tube to show the deflection of an electron beam by electric fields

Apparatus

1 fine-beam tube and base	items 235, 140 (or 61, 62)
1 H.T. power supply	15
4 12-volt batteries‡	176
1 L.T. variable voltage supply for a.c.	59

‡ Batteries are needed here, to give a steady deflection. The output of an ordinary d.c. power supply is rectified a.c., not fully smoothed; the electron stream would show the rapid changes of its voltage in each cycle of the original a.c.

(Remember that with the Teltron tube one plate is connected to the gun muzzle which may be at high voltage relative to the cathode.)

Procedure

Connect the 12-volt batteries in series and join a centre tap to one of the deflecting plates. Connect a lead from the other deflecting plate successively to different tapping points on the batteries to show the effect of changing the voltage.

Ask pupils what they would see with alternating voltage, which changes rapidly.

Then show deflection with alternating voltages. Connect the a.c. output of the L.T. variable-voltage supply to the deflecting plates. Increase the voltage slowly from 0 to 25 V. (Note that one of the deflecting plates is connected to the anode.)

Magnetic deflection? The next effect to show would be deflection by a magnetic field. But this plays an essential part in Year 5, when motion in an orbit is discussed and used for a measurement. So we suggest postponing this demonstration to Year 5. Teachers who wish to show it now will find details in *Teachers' Guide 5*.

THE ELECTRON: MILLIKAN'S EXPERIMENT

The importance of this experiment Electrons are common objects in modern physics, and even young pupils talk glibly of them. Yet *none* of the experiments with *streams* of electrons provide convincing evidence that electricity comes in atomic particles. Measurements of e/m, which will come in Year 5, merely show a constant proportion of CHARGE to MASS for all such streams.

{Experiments like the Teltron diode demonstration only show that hot filaments emit negative electricity which can travel across a vacuum. Even the photo-electric effect fails, in the usual demonstrations, to show individual electrons—or, for that matter, individual photons.}

The experiment that really shows 'atoms of electricity' is Millikan's experiment. Since the idea of universal electron charge is essential to any picture that we are now building in atomic physics, we regard this experiment as a very important part of our teaching. It should come now and not be postponed till Year 5, because a well-digested understanding of this part of our atomic knowledge will be needed at the beginning of Year 5. Teaching Millikan's experiment then, even though only by a short film, would add a serious burden to the new work on circular orbits and e/m. However much teachers are tempted to postpone the Millikan story, we hope they will not do so.

METHODS OF SHOWING MILLIKAN'S EXPERIMENT

{**Individual viewing** A number of forms of Millikan's apparatus have been manufactured and offered for use in school and university laboratories. Again and again there is a rumour of a still simpler form that 'really works easily' in pupils' hands. There are improvements, but the new forms still require one or two pupils to work with them undisturbed for some time.}

{Even in demonstrations, the most well-behaved apparatus, set up by the teacher and kept running with a visible droplet, can only be seen by one pupil at a time. The thing to be seen, a tiny moving or stationary speck, is even more difficult for a beginner to see quickly—if he is to appreciate its importance—than the Brownian motion glimpsed in a hurry. The difficulties are intrinsic: however much the apparatus is simplified and improved there will remain the problem of individual watching. If our pupils were devoted physicists with full appreciation of the importance of this experiment, the long delays in such viewing might be worth while; but that should be at A-Level. The demand of time for pupils to look, and time and care for the teacher to set up the apparatus, are too great for use of the real apparatus in classes at this stage of O-Level.}

{Where a school already has apparatus for a Millikan experiment we suggest it might be used by some pupils as a luxury option in Year 5 if specially keen pupils can give it the time it needs.}

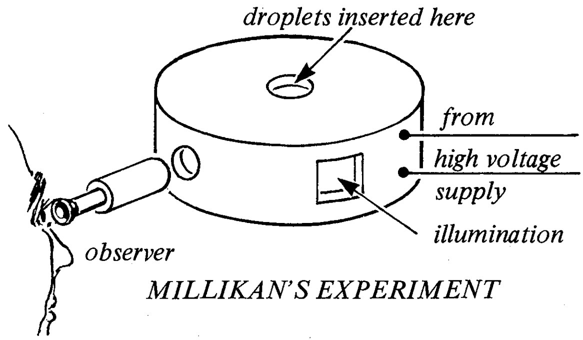
{**Closed-circuit TV** There are possibilities of demonstrating a real Millikan experiment by closed-circuit TV. That can be done at considerable expense; and if it is done with sufficient explanation it may be slightly better than showing a film. Pupils can see the apparatus; they can come up to it afterwards and look at details; and a few keen pupils could use the apparatus at other times. But that again seems too expensive a way of teaching this one part of our course, however important. It is not only expensive in money for equipment: it also makes considerable demands on the teacher's time. Therefore, we do not recommend it except where a school already has the Millikan apparatus and already has closed-circuit TV for other purposes.}

{**Films** And yet the experiment is vital. It is the key experiment in the development of an atomic story. Other evidences of atomic nature—of matter, of radiation—are things that we have to give as assertions at this stage, or, as in the case of e/m, go through a long calculation that threatens to spoil any sense of clear conviction in our pupils. But Millikan's experiment can show young people clearly that electric charge comes in 'atomic' form. Therefore we resort to film—celluloid teaching.}

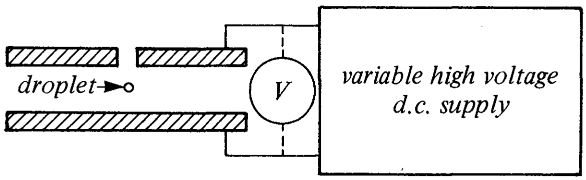
{That is a far less direct form of teaching than an individual experiment, but far better teaching than description and assertion in a book.}

That is why a Nuffield film* has been made, to show the real experiment in a simple way. The method used is described below.

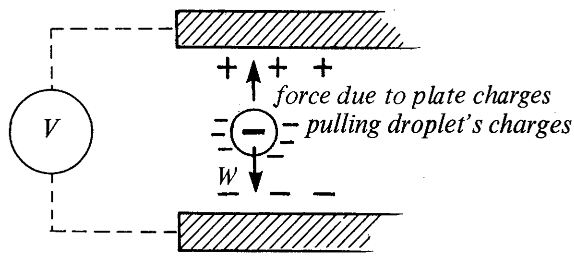
The Nuffield Millikan film In our version of the experiment the oil-drop is replaced by a tiny plastic sphere of known size and density. We call the floating sphere 'the little balloon'. It falls slowly against air friction in a shallow



MILLIKAN'S EXPERIMENT



space between two horizontal plates. A battery connected to the plates maintains a vertical electric field in the space. The tiny floating sphere is given an electric charge, and the electric field between the plates is adjusted by changing the potential difference until the upward pull of the electric field on the charge on the sphere exactly balances the downward pull of gravity. The sphere is held poised in mid-air in the field of view.



Then the charge on the sphere is changed, and the p.d. between the plates is varied until the sphere is again poised. That is repeated after several changes of charge. Thus pupils see a set of different voltages applied to the plates as the sphere takes on different charges. Each time, the voltage is just enough to hold the sphere poised.

The charge on the sphere is changed by ionizing the air around it and letting the sphere pick up some charges from ions. (If we bring a radioactive source near it makes many ions in the region between the plates; or we can ionize with a discharge from a small Tesla coil—a 'vacuum tester'.) If the electric field is maintained those ions are quickly swept away and we may have to wait some time before the sphere can pick up a charge.

* There is also a film made by the P.S.S.C. to show Millikan's experiment. It is a very fine film; but it adopts a different scheme of teaching and we do not suggest its use in our programme.

If the electric field is turned off, the sphere falls slowly through air containing ions and soon picks up a charge. It often changes its total charge by several electron charges.

In each case we assume that when the sphere is poised, the upward pull of the electric field on the charge exactly balances the pull of gravity downward. Therefore:

weight of sphere = (charge) × (electric field strength)

because the field strength is the force on unit charge.

Film 141 Millikan: 'Are there electrons?'

The Nuffield film is 16 mm, with colour and sound, ref. No. 21.7772. It is obtainable from The Rank Film Library, Rank Audio-Visual Ltd, P.O. Box 70, Great West Road, Brentford, Middlesex.

[There is also a short 8 mm film loop *'Are there electrons? (The Millikan experiment)'* Rank Film Library ref No. 290316. This simply yields data. Teachers would need to explain in detail and show the *real* apparatus, so we recommend the full film.]

The full film may be too long for Year 4 pupils. Teachers will find on running it through beforehand that there is a good stopping place. Teachers may prefer to switch off the sound track and give their own description.

In deriving the essential atomic nature of electricity from Millikan's experiment we do not need to teach or use the concept of field strength explicitly. We can talk more loosely about forces, charges, and voltage and convey the main argument thus, as in *Pupils' Text*:

★ ★ ★ ★ ★

The battery drives equal and opposite charges onto the two plates, + above and − below. If the little balloon has a − charge, those charges on the plates together push and pull the balloon upward (while gravity pulls it down). *Two* batteries in series, with *twice* the voltage, will drive twice as much charge onto the plates. Then the upward force on the balloon will be twice as big. The voltmeter tells us how much charge we are putting on the plates, how big the force on the balloon will be.

But if we change the charge on the balloon, that will alter the upward force too: doubling *that* charge will double the upward force exerted on the balloon. In every case we shall make the upward force balance the weight of the balloon, the downward pull of the Earth on it.

There are two factors that affect the upward force:

a. The charges on the plates, which we can estimate by the voltage V;

b. the charge on the balloon (which we want to find out about).

We multiply those two factors (a) and (b) in finding the upward force, and the result must *always be the same* if the upward force always balances the balloon's net weight.

(VOLTMETER READING V) × (BALLOON CHARGE) = same answer every time.

$\therefore$ BALLOON CHARGE = (constant).$(1/V)$.

★ ★ ★ ★ ★

Analysing the measurements Therefore the charges on the sphere in successive poisings are proportional to values of $1/V$.

Thus we can calculate the numbers which represent the total charge on the sphere—on an arbitrary scale—by taking the reciprocals of the voltages. We do that, and then discuss with pupils the information about electric charges that we can extract.

As in Millikan's original experiment, we cannot see straight away from the measurements that we have discovered universal electrons. We have to find out whether our measures of charge are all multiples of some universal unit. That seems obvious to us, who already know the problem and the solution, but it is a difficult investigation for pupils to understand. So we tell them the fable of the *'Eggs in the Paper Bags'* (see *Pupils' Text*).

With that kind of illustration, pupils should be ready to join in the analysis of the film. The film first shows many spheres, with different charges, moving under gravity alone and with electric fields applied. Then one sphere is singled out and poised by adjusting the voltage between the plates.

The charge on that sphere is changed again and again, by letting it collect ions, and after each change the voltage is adjusted to poise the sphere. The reciprocals of those voltages are then taken as measures of the total charge on the sphere and, like the eggs in the bag, they suggest strongly that in every case we have whole-number multiples of some basic charge.

Then pupils should look at the values of $(1/V)$ obtained from the film and see whether those values suggest a basic unit charge and multiples thereof. One method is use a piece of good luck (which occurs in the film) when in one of the measurements there is a single electron excess charge on the 'balloon'.

In the film, successive voltmeter measurements are, in volts:

337 425 840 564 1694 ...

The reciprocals of those, when multiplied by 1000, are:

2.97 2.35 1.19 1.77 0.59

Try dividing by 0.59 hoping it relates to one electron charge

5.03 3.98 2.01 3.00 1.00

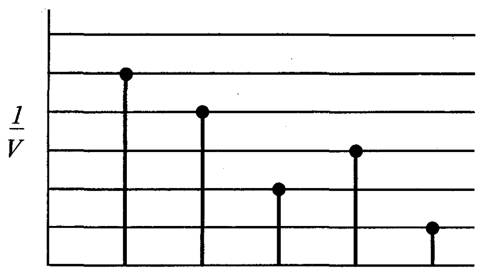
There are suggestions of whole-number charges

5 4 2 3 1

Another method: use the *differences* of $(1/V)$:

$-0.62 \quad -1.26 \quad +0.58 \quad -1.18$

Those differences are easier to see on a bar graph:



successive poisings

Our principal objective here is to let pupils see that all the charges on the specimen sphere could be treated as made up of a few 'electrons' that are all alike. We want to give the idea of a universal basic charge.

We are *not* at the moment trying to measure that charge. In fact, pupils will have to take our word for the absolute measurement.

NOTE ON PLASTIC SPHERES FOR MILLIKAN'S EXPERIMENT

{In any teaching version of the Millikan experiment we should take advantage of a modern development. We can use extremely tiny spheres of solid plastic instead of the droplet of oil used by Millikan.}

{Some years ago, chemical manufacturers discovered that they could make batches of very small spheres of uniform size. These are now supplied to the users of electron microscopes, for calibration. We can obtain a large quantity of these that are all the same, known size. Thus, if we lose the 'droplet' we can start again with another; and we can use the known size of the 'droplet' to calculate its weight without having to appeal to Stokes's Law.}

{The size of these spheres can be measured by comparing them under an electron microscope with something larger and that with something larger still at lower magnification, and so on by 'bracketing' into the optical field; so that ultimately we know their size compared with a centimetre rule. That size, for a uniform batch, is supplied by the makers.}

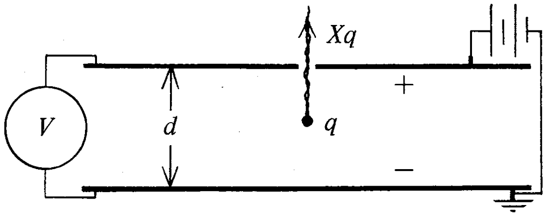
{A rumour arose some time ago that the use of these plastic spheres in a Millikan experiment is deceitful 'because that is how the spheres are measured'. It would be possible to measure the spheres by their terminal velocity in air—though one would hardly bother to charge them and impose electric fields—but this is not the standard method. Nor would such a method invalidate our form of Millikan's experiment, because we aim at showing the existence of universal atomic charges of electricity, and not at measuring the absolute value of e.}

NOTES ON FIELD STRENGTH

With faster groups we might deal with field strength fully, as below. (That will also be useful in qualitative discussion of the effect of electric fields on electron streams.) Only if pupils would enjoy this algebraic form should it be offered to them.

The field strength is the force on unit charge placed in the field, measured in newtons per coulomb.

We can measure the field strength between the plates by using a voltmeter and a metre rule. Imagine a tiny charge q coulombs in the space between the plates. If the field strength is X (in newtons per coulomb), the force on q is Xq (in newtons). That is the force with which the electric field drags q downward from one plate to the other.



Attach an imaginary thread to q, pulling q upward, from the lower plate to the upper plate, a distance d, against the pull of the electric field. We can calculate the WORK which measures the energy transfer *FROM* the agent pulling the thread *TO* the electric field (and the battery maintaining it).

The work is (force)$\cdot$(distance), or $Xq \cdot d$.

But in making that transfer we have dragged a charge q from one plate to the other. If the potential difference between the plates is V volts, every coulomb dragged from plate to plate transfers V joules of energy. And q coulombs transfers Vq joules of energy. This is another statement of the WORK.

Therefore, $Xq \cdot d = Vq$. Therefore, $X = V/d$.

Thus by connecting a voltmeter across the plates and measuring the distance between them we can calculate the field strength V/d.

Since the field strength is directly proportional to the voltage between the plates, we can use the voltmeter reading as a measure of the field strength.

Each time the sphere is poised:

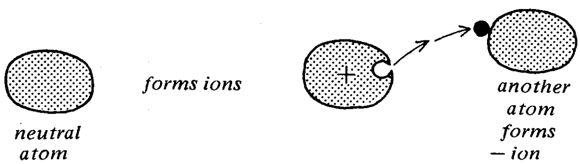
the weight of the sphere, which remains constant,
= [charge]$\cdot$[field strength]
= [charge]$\cdot$[V/d].

Therefore, [charge] = [constant weight]/[V/d].

IONS IN AIR

We should begin the discussion of atom models in this year. If pupils do not hear about ions and see the Millikan film until Year 5, unfolding the story of atom models will be too rushed and crowded—there will not be time to digest and enjoy the successive stages.

Our first model follows demonstrations with electron streams. We show that air can be made conducting, and we describe ions, by assertion, as atoms or molecules that have lost or gained an electron. This picture is useful:



Remind pupils they have already heard of charged carriers in electrolysis. And when they see tracks in a cloud chamber, those are lines of tiny drops—of water or alcohol—that have condensed on ions. 'Nuclear bullets' from radioactive atoms have hurtled through the wet air detaching an electron from atom after atom.

Teachers may wish to comment, in terms of electrons and ions, on sunburn, ultraviolet light and ozone; X-rays, and on radiation dangers and damage.

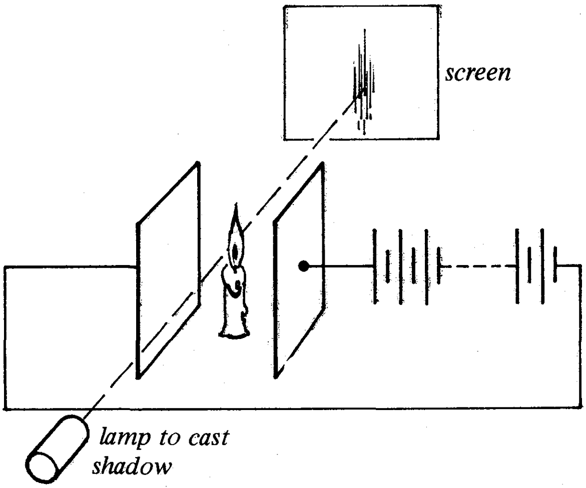
Show pupils gases conducting in a candle flame—the flame may even split and suggest both positive and negative carriers.

Show air made conducting by bombarding missiles from radioactive sources.

Demonstration 142 Ions in a candle flame, driven by an electric field

Apparatus

1 pair metal plates with insulating handles	item 65
1 E.H.T. power supply	14
1 compact light source	21
1 candle	
1 translucent screen	46/1
1 transformer	27
2 retort stands and bosses	503/4/5



Procedure

Fix the plates in vertical planes; parallel to each other and 5 to 8 cm apart with their insulating handles in bosses on retort stands. Light a candle flame a little below them. Set up the compact light source a metre or more away so that a clear shadow of the plates and the flame falls on a screen behind.

When a high p.d. is applied to the plates from the E.H.T. power supply, the flame divides into two parts, one towards the positive plate and one to the negative.

CURRENT CARRIED BY IONS

To show the current carried by ions in air we need a far more sensitive meter than an ordinary microammeter. We need a micro-microammeter, or something more sensitive still. That should be a *simple* device; so we just let the tiny current charge up an ordinary electroscope. We disconnect one plate from the supply and join it to the leaf of an electroscope, and connect the case of the electroscope to the supply. Pupils watch the electroscope leaf rising slowly when a flame is brought near the space between the plates. After the supply is removed, the flame produces no such effect. But if the electroscope is charged up and the battery is then replaced by a wire, pupils see the electroscope losing its charge when a flame is brought near the space.

It is possible to convert the electroscope to a micro-microammeter that will indicate a current by a steady deflection. We connect the leaf to the case by an extremely high resistance, such as a strip of ordinary paper. The electroscope charges up to that voltage at which the leakage current through the resistance exactly matches the current being fed to it. (This is, in a sense, the inverse of our way of making an ordinary voltmeter from a milliammeter. Here we are making our current-meter from a true voltmeter.)

D.C. amplifier to measure ion currents? There are now electronic meters, d.c. amplifiers, that have enormous sensitivity. The device takes tiny input currents—as small as 10^{-14} amp—and amplifies them to be read on an ordinary moving-coil meter. It can even drive a large demonstration voltmeter as a 'slave' indicator. These are increasingly popular but we do not recommend one for O-Level—it would be too magical a 'black box'.

Demonstrating ionization by radioactive material If the lab has a suitable source, show now—in anticipation of Year 5—radioactive material ionizing air.

{Though the *nuclear changes* involved in radioactivity now seem more thrilling, the *ionization produced* is the property through which radioactivity was discovered. It is the basis of measurement today; and it is the effect that makes radioactivity hazardous. It provides the mechanism for cloud-chambers and spark-counters which pupils have met.}

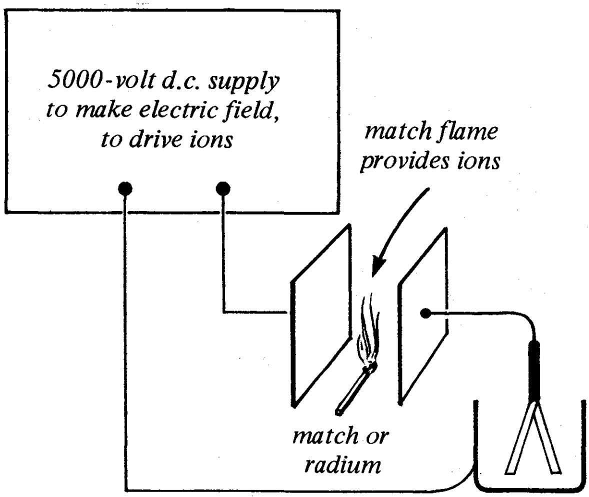
{With a safe source the rate of ionization, even in quite a large volume, will be too small to provide a current that can be measured on any ordinary galvanometer. The current has to be shown as a leakage current carrying charge to or from a simple electroscope,* as for the flame ions. That unfortunately makes the demonstration look different from one of ordinary, larger currents.}

*{It would *not* be wise to use a special oscillating-leaf electroscope (a Zeleny or Wulf type). For one thing, that would burden the teaching with the weight of special explanations. Also, such instruments can be very misleading when we come to show radioactivity. The regular pulsing of the leaf, faster for stronger radioactive sources, may be confused by pupils with the random pulsing of a counter by individual particles. It would be most unfortunate, when we are trying to show a few examples of the particulate nature of the microphysical world, if we ran any such risk of confusion. If a simple electroscope will not suffice for the ionization available, it is better to show no experiment.}

Demonstration 143 Radium makes ions in air

Apparatus

1 pair metal plates with insulating handles	item 65
1 E.H.T. power supply	14
1 gold-leaf electroscope	51A
1 hook for electroscope	51J
5μCi radium source	16
2 retort stands	503–504
2 bosses	505
1 holder for the radium source	196



Procedure

a. Flame provides ions Fix the two metal plates in vertical planes parallel to each other and about 5 cm apart. Connect one plate to the positive terminal of the E.H.T. power supply through the safety resistor; the other to the leaf of the electroscope through the hook. Connect the case of the electroscope to the negative terminal of the E.H.T. power supply, which is itself earthed.

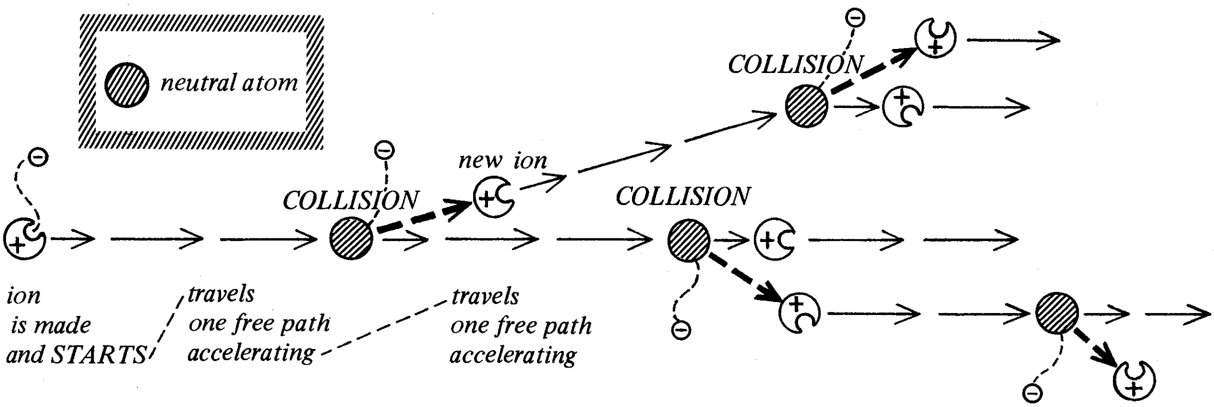
Apply about 2 kV to the plate. The electroscope leaf will show an inductive effect and should be earthed momentarily.

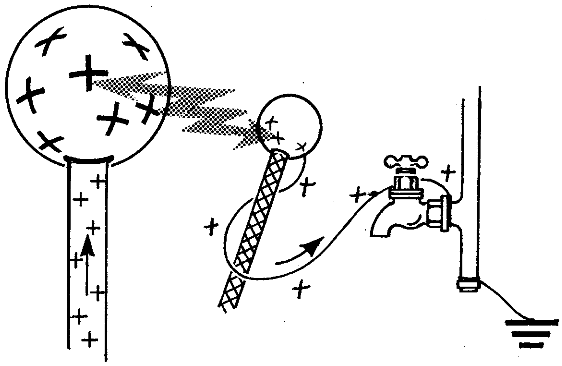
(i) Hold a match flame just below the plates. Pupils watch the leaf.

(ii) Remove the connection to the charged plate and switch off the power supply. Earth the plate that was charged and use a second match to show the discharge of the electroscope.

b. Alpha particles make ions Repeat the experiment using a 5μCi radium source, held between the plates.

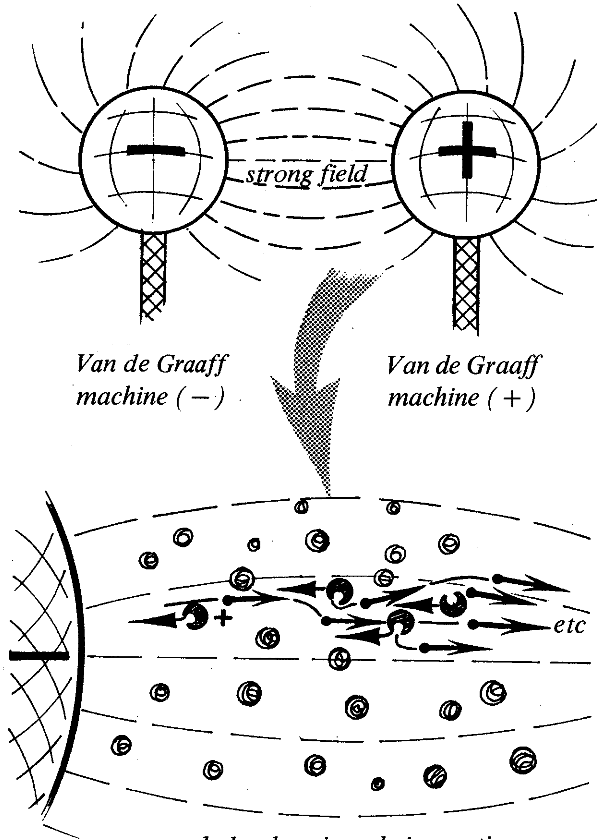
The electroscope's leaf is easier to see as a shadow on the glass front of the instrument itself. Cover the front with translucent paper. Place a 12 *V* 24 *W* straight filament lamp about $\frac{1}{2}$ metre behind the electroscope. This gives a fine sharp picture.



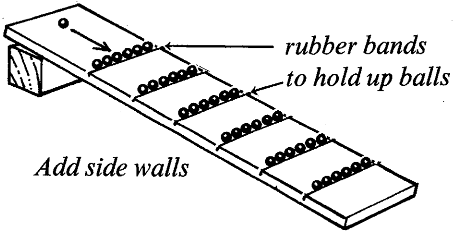


Inelastic collisions: multiplication of ions
Suppose we apply an *electric* field to a region where ions are *formed*. We picture an ion—driven by the field—accelerating, gaining kinetic energy until it hits a neutral molecule, where it gives up its gains in an elastic collision. Thus its motion is a series of accelerated runs, each of length one free path.

In a *very strong* electric field an ion can gain enough K.E. between one collision and the next to make an *inelastic* collision and knock an electron off the next molecule it hits thus making a new pair of ions. That process of ionization by collision multiplies the number of carriers, so the gas conducts well. The ionization may mount up exponentially in a chain-reaction—then we have a spark. The actual mechanism is much more complicated than that, but we should give pupils a simple glimpse of the picture. (Where there are ions there will be photons of ultra-violet light and perhaps X-rays; the negative ions will be electrons part of the time, and therefore much more mobile; and excited atoms will also play an essential part.)



a spark develops in a chain reaction



Model of chain reaction in a spark. The rows of balls represent gas molecules regimented one free path apart. At a large tilt of the board one 'ion' will make many more in a chain reaction.

Air molecules make elastic collisions Make it clear to pupils that collisions between air molecules at room temperature are quite unable to produce ions: they will be perfectly elastic every time.

Electron·volts In simple discussions of atomic events, 'electron·volts' are still useful units. Pupils will meet them in books so we should say: one electron·volt (eV) is the energy gained by one electron charge falling through a p.d. of one volt. So it is 1.6×10^{-19} joule.

For a collision to detach an electron and make a pair of ions, the colliding particle must bring in enough kinetic energy—the amount needed ranges from a few eV for some metals, to 20 or 30 eV taken from a fast particle to make a pair of ions as it rushes through air.

The average K.E. of air molecules at room temperature is about 0.03 eV—no wonder their collisions are completely elastic.

Since a gas molecule's K.E. varies as absolute temperature, we should expect an ionizing collision to be rare indeed even at ten times room temperature, 3000 K. On the other hand, a simple electron gun like the one in the fine beam tube, shoots out ionizing projectiles with many times the K.E. needed to make ions—and that is why the fine beam tube shows the path of the beam by a glow.

A LOOK INTO THE FUTURE

ELECTRONS THEMSELVES

In watching Millikan's experiment pupils have seen evidence of the electron *charge* as an atomic unit of electricity. What have they seen of electrons themselves, as particles of minute mass carrying such a charge?

The sphere or oil-drop in Millikan's experiment collected its charge from ions—air molecules near by that had gained or lost an electron or two. The sphere may have acquired its original charge by contact ('friction') as it entered the apparatus. Millikan himself also changed the charge on his oil-drop by ejecting photo-electrons with ultra-violet light or X-rays. All the ways of providing charge agree with the idea of a universal unit of charge. But they do not tell us about the electron's mass; and at most they make only a vague suggestion about the part played by electrons in atomic structure.

To learn about electrons themselves we experiment on streams of electrons with the fine beam tube and the demonstration diode; and we should look at pictures of the tracks of electrons in a cloud-chamber or a bubble-chamber.

We tell pupils that later experiments, as well as Millikan's experiment, do suggest that a stream of 'cathode rays' is a stream of small particles, all alike, carrying a basic electric charge which we never normally find subdivided. We should say that some compelling, though rather indirect, evidence will come in Year 5. We shall measure e/m for a stream of cathode rays, and find it huge compared with e/M for hydrogen ions.

Combining that with knowledge from Millikan's experiment we guess that cathode rays are streams of tiny particles, all with the same negative charge, all with the same tiny mass—a fraction of any atom's mass. We are sure, then, that we have discovered chips from atoms; and we call these chips electrons.

Then we see more evidence of electrons. If we give them enough energy we can count them one by one with a Geiger counter or the equivalent. We can observe the tracks of individual high-energy electrons in a cloud-chamber. These demonstrations are in Year 5.

Electrons' mass and speeds Looking forward to next year, we might tell pupils that their e/m experiment then will also tell them the speed of electrons issuing from a 'gun'.

Although an electron carries a small charge, its mass is so minute that we can give it enormous accelerations by using the ordinary electric fields at our command. Pupils will be able to calculate the speed that, say, a 100-volt battery can give electrons.

We might warn them that they will need to remember some things they already know:

that kinetic energy is calculated by $\frac{1}{2}mv^2$

that a p.d., measured in volts, is the energy transfer per coulomb, measured in joules per coulomb.

They will need to learn about the effect of a magnetic field on a stream of charged particles. Then they will be ready to measure e/m for electrons, and their fantastic speed. They will see for themselves why we think electrons are only tiny chips off atoms.

Currents in wires We can, if we like, describe, in terms of electrons, the events inside a wire that is carrying a current. In our picture, most of the electrons in a metal wire are anchored firmly to atoms in the crystal lattice; but some of them are detached and live a life rather like molecules in a very hot gas, moving to and fro in the crystal lattice at fantastic speed. (We should be careful not to say the electron gas is quite like a gas of ordinary molecules at room temperature. The statistics are different, and the speeds are unexpectedly high.)

The electric field along the wire, produced when we attach a battery to the wire, drives that hurtling horde of electrons with a slight general drift, which makes the electric current.

Evidence of electrons in wires? If a pupil asks us how we know the electrons are there, we should tell him the evidence is awkward. We may remind him that he has heard about electrons 'boiling off a hot filament'.

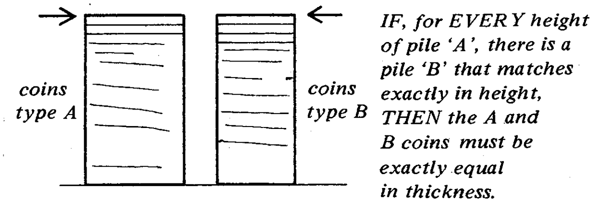
{We might even tell a very able pupil about the 'Hall effect' in which a magnetic field applied *across* a wire carrying a current produces a very small voltage across the wire in the third direction, perpendicular to current flow and magnetic field. That voltage is due to crowding of electrons by the catapult push of the magnetic field. It is in a direction which shows that we have a flow of negative charges. The effect is too small in metals to demonstrate easily and, unfortunately, there are exceptions, which modern quantum physics can explain, in which the Hall effect takes a reverse direction. There are many exceptions among semi-conductors, where the moving things may be 'holes' instead of electrons, a hole behaving like a positive charge. Therefore we advise against quoting this evidence. Although a Hall-effect demonstration with semi-conductors is fairly easy, it would be most unsuitable here where we are discussing the motion of electrons in metals.}

Electrostatics and mobile electrons We can describe electrostatic behaviour in terms of electrons that are free to move in metal. Charges at rest reside on the outer surface of metal objects (unless we have parked a charge on an insulating stand inside some hollow metal container).

When charges move, we say it is electrons that move, while positive atom-cores stay fixed. That makes electrostatics a little more complicated, though much more real to many a pupil, and much more exciting for those pupils who picture electrons running about like beetles all over the surface. We may give such descriptions but we should raise a warning flag. (See 'Teaching Electrostatics with Electrons' in the General Introduction issued with *Teachers' Guide 3*.)

Positive charges in atoms We know that atoms are electrically neutral. They experience no net force in strong uniform electric fields. (Of course *ions* do experience forces, but they have a whole electron charge.) Therefore we believe that whatever positive charges there are in an atom must exactly balance the negative charges of the electrons that are there.* When, in later studies, we decide a hydrogen atom has one electron, a helium atom 2, . . . an oxygen atom 8, . . . and so on, we decide that the rest of the atom, the positive nucleus, must have exactly 1, 2, . . . 8, . . . times an electron's charge, but of opposite sign.

{* The exact equality is vouched for by the failure of electric fields to exert *any* net force on small uncharged objects, which consist of a vast number of atoms. A 'Millikan-Experiment' test on a collection of oil drops of many different sizes shows some that are charged. We know they are charged because an electric field affects their fall; and our measurements show the charges are all multiples of e. But some drops are uncharged, and even a very strong electric field has no effect on their fall, showing that they have not even a small fraction of e as net charge. Since we observe that for different sizes of uncharged drop, the neutrality cannot be due to a chance adding-up of fractions to an integer; so the equality of + and − charges in those drops, and thence in atoms, is vouched for.}



{The argument here is easier to understand if we apply it to comparing thicknesses of two types of coins, or, say, dominoes. We make a pile of 50 of type A. If we can match that exactly in height with a pile of type B, we think the B items *may* have exactly the thickness of A items. But the B pile might contain 49 items each 1.02 times as thick as an A item—and there are other possibilities. But if we *always* secure exact matching of A and B piles for many different total heights we are forced towards the conclusion of equality.}

ELECTRONS AT WORK: CATHODE RAY OSCILLOSCOPE

If there is time at the end of this Year, pupils might have cathode ray oscilloscopes to work with, on their own, for class experiments. The reward for skill in manipulating the controls, and making the trace obey, should be a small microphone, to be connected to the oscilloscope so that it will show voice waveforms. Musicians should be encouraged to bring their own musical instruments. Pupils learning French might practise the light 'u' as in 'tu' and derive some phonetic advantage from watching the results of their efforts.

Pupils might return to the demonstration of a diode as a rectifier and see its action on the oscilloscope now, if not earlier.

Pupils who are interested might construct a 'full wave rectifier' and try that on the oscilloscope.

ELECTRON GUN

When pupils saw negative electricity streaming across from hot cathode to plate in the Teltron diode tube, they had, without knowing it, discovered an electron gun. If a hole is drilled in the plate, a stream of electrons will go out through the hole; and we have a 'gun' that can fire a stream of electrons into other apparatus.

Electrons boil off a hot filament in a vacuum, emerging with a little kinetic energy, and collect nearby in a cloud which repels the continuing supply of electrons back to the filament.

To fire a stream of high-speed electrons out from the gun, we apply an electric field to accelerate them in the space between filament and plate—which we may now call the gun muzzle. If the electric field is strong enough it sweeps electrons across to the plate as fast as they evaporate and there is no discouraging cloud round the filament. With a weaker field, there is a cloud, from which we can pull a fast stream (of uniform energy) by interposing a grid with a strong accelerating field beyond.

If the battery maintains a p.d. V (in volts) between filament and plate, an electron with charge e (in coulombs) which just escapes from the filament and is dragged across to the plate gains energy $e \times V$ in *coulombs* $\times$ *joules/coulomb* from the field. So it arrives at the plate with energy Ve joules.

If such an electron reaches the plate where we have drilled the hole that serves as gun muzzle, it flies on through the hole into a region where it finds no accelerating field. (We may connect the plate to the far end of the tube or any other apparatus at which our gun is firing.) So the electrons in the stream emerging from the gun continue with constant velocity thereafter—Newton's First Law—unless we apply further fields to the stream.

In what form do those flying electrons carry the energy that the accelerating field has given them? As seen by us, stationary observers, all the energy they have gained is just kinetic energy $\frac{1}{2}mv^2$. As the electrons travel from filament to gun muzzle in that electric field, they gain more and more K.E. The energy with which they leave the filament is trivial, so we say that their final K.E. when they emerge from the gun muzzle is the energy given them by the field. For one electron that is Ve.

$$\text{Then } \tfrac{1}{2}mv^2 = Ve$$

We picture the electrons in the stream from the gun flying on with constant velocity given by the equation above, until they hit a target or are given other momentum by some applied field. When they hit a target and are brought to rest, their kinetic energy is nearly always converted into heat in the target—only occasionally is the energy radiated as a photon of light or X-rays.

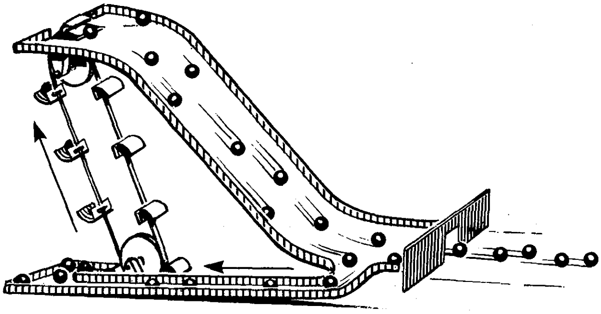
Pupils cannot at present calculate the speed v, because they do not know the value of e/m. They will be able to measure e/m and v in Year 5, with the help of a magnetic field to deflect a beam of electrons into a circular orbit that can be measured. Before that, we would have to announce the value of e/m (about 1.8×10^{11} coulomb/kg) if we wanted pupils to calculate v now—and that would seem unfortunate anticipation.

We know the value of e/m. If we insert it, we obtain amazing results: v for electrons from a 100-volt gun is about 6 million metres/second, about 21 million kilometres per hour.

Although we do not advise teachers to announce the value of m and ask pupils to calculate v, we suggest it would be good preparation for Year 5 to lead up to the equation $\frac{1}{2}mv^2 = Ve$ and point out the need for one more measurement before we can find the speed of electrons from a gun of known voltage. (Direct measurements of v are possible, by a time-of-flight method like our estimate of a bullet's speed with the scaler; but those are rather difficult.)

We might start some thinking now with a sketch of an analogue model of electrons 'falling through' a potential difference.

Model Imagine a toy gun for marbles made by using a sloping plank which represents the region of electric field from hot filament to gun muzzle. Provide a reservoir of marbles at the top of the plank and let them run down to a wall at the bottom—here they stop and collect in a pool where an escalator acts as a battery and returns them to the top. Make a hole in the wall, so that some of the marbles arriving at the bottom of the slope meet the hole and go straight through and continue along a level table at constant speed.



We speak of electrons as *'falling through' the p.d.* between filament and gun muzzle just as the marbles in the model *fall through the height h* and gain K.E. which is given by $\frac{1}{2}mv^2 = mgh$. *Pupils' Text* gives a suggestive description, and mentions electron·volts.

APPENDIX 1

MULTIFLASH PHOTOGRAPHY

MULTIFLASH PHOTOGRAPHY IN GENERAL

In each case the highlighting of the body being photographed against a dark background is necessary to ensure good contrast in the picture. The successive photographs of the event at regular time intervals on the same negative frame are achieved either using constant illumination and strobing the camera with a motor-driven stroboscope or using intermittent illumination, or by strobing the light from a projector that illuminates the scene.

MULTIFLASH METHODS

In Year 4 multiflash photography plays a large part. The technique advocated uses an ordinary camera and a motor-driven strobe disc.

Some teachers prefer other techniques, for example using a xenon stroboscope. Details are given below in Method 2.

Details of processing the films are given in Appendix 2.

Method 1: Strobe photography using an ordinary camera and a synchronous motor-driven strobe disc

Camera A camera focusing down to $1\frac{1}{2}$ or 2 metres is required. Its lens must have an aperture of at least f8, though larger apertures are to be preferred.

The shutter must have T or B setting. The B setting is more convenient.

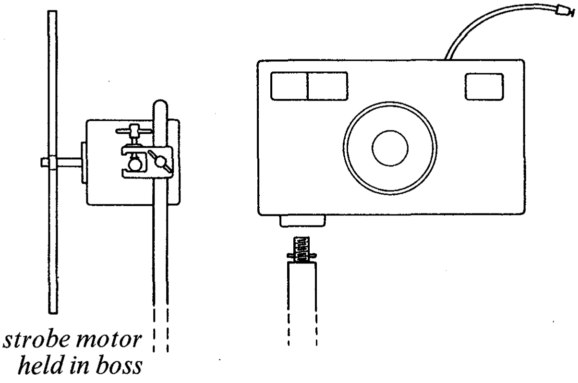
The description here is for a camera which takes 35-mm film.

The developing and printing process described in Appendix 2, which can be carried out in front of the class in daylight without blackout, is only suitable for 35-mm film. (More traditional methods would be necessary for 120-size film.)

Unless the camera has a reflex viewfinder, it is as well to check the field of view by putting a strip of translucent material in the position normally occupied by the film and opening the shutter with the B setting to see directly whether all the field you wish to photograph is in view. Once this is done a note can be kept of the camera distance and the area of view covered.

Set up the camera firmly, level with and about $1\frac{1}{2}$ m away from, the moving object. Measure the distance carefully and set the lens mount for this distance.

Supports A steel rod about 20 cm long × 1 cm diameter, with one end threaded to enter the camera's tripod bush makes an ideal support for the camera and allows it to be used with a normal stand, boss and clamp.



Hold the rod of the stroboscope motor in an ordinary boss on a stand.

The stands used as supports should be as massive as possible (extra loads on each base will help). For extra height clamp the stands on lab stools, rather than use very tall stands.

Exposures Then fit the motor with the appropriate disc. Place it with the disc 1 or 2 cm in front of the camera lens. (The 5-slit disc gives an interval of $\frac{1}{25}$ sec, and the 6-slit disc an interval of $\frac{1}{30}$ sec between shots.)

The number of exposures can be varied by covering unwanted slits with black adhesive tape. (This should be done symmetrically.) This will enable one to choose a suitable number of exposures to appear in the final picture.

For example, with a synchronous motor running at 300 r.p.m.

the 5-slit disc with

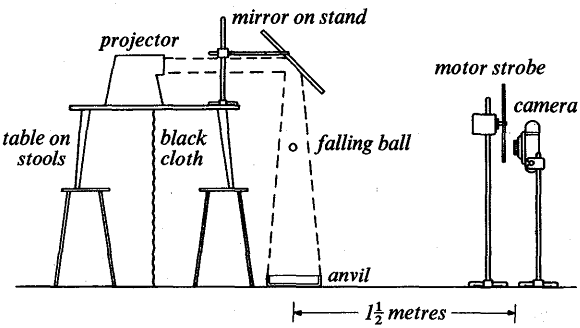
1 slit open gives 5 exposures per sec
2 slits open gives 10 exposures per sec
5 slits open gives 25 exposures per sec

The width of the slit controls the sharpness of the images obtained and the narrowest slit consistent with adequate illumination should be chosen.

Lighting The scene may be lit by a 500 or 1000 watt 50-mm slide projector, placed so that the beam of light illuminates the whole of the action without (a) illuminating the background;
(b) spilling light on the camera and strobe. Photofloods can be used, but will require careful screening to avoid these faults.

A clean blackboard may be used as background. A matt black cloth surface would give better contrast, but that is not essential.

In experiments on free fall it is best to use a mirror held in a stand to direct the beam of light down the path of the falling ball. It is not advisable to tilt the projector itself through an angle exceeding about 45° from the horizontal.



Moving trolley Probably the best object for illumination is a dowel rod (as supplied with trolleys covered with chrome Sellotape or kitchen foil).

Rolling ball For motion down a hill, use a polished steel ball—diam. 2 cm or more. Also use a ball as a projectile. The light reflected from the ball, which acts as a convex mirror, appears to come from a tiny bright virtual image of the lamp; that is a point-object so far as the camera is concerned.

Free fall A steel ball is useful. If it is dropped on an iron anvil tilted at a slight angle to the horizontal, a series of bounces can be photographed.

To photograph a simple pendulum use a U2 cell + lamp as the bob. Turn the camera so that the broad side of the frame is horizontal.

Measurements In some cases it is useful to include a scale placed near to the path of the moving object. A boldly marked scale about a metre long is best. A metre rule may be adapted by sticking 5-cm strips of paper on it, every other 5 cm (0–5, 10–15, . . .).

Chalk lines ruled at 10-cm intervals on the blackboard, or on black paper are useful.

The procedure for a falling ball:

1. Switch on the lamp having darkened the room wholly or partially.

2. Check the focus of the camera lens and select the maximum lens aperture, say f 3.5.

3. Make sure that the camera covers the full area desired.

4. Put strobe motor and disc in front of the camera and switch on.

5. Set the shutter to the 'B' position.

6. Count down (3–2–1–0) and open the shutter just before the assistant releases the ball. Hold the shutter open.

7. Close the shutter as soon as the ball has completed its motion.

8. Wind the film on.

9. Repeat the exposure two or three times using smaller apertures to find the optimum and to provide spare negatives for later use.

Method 2: Using a xenon stroboscope and a 35-mm camera

Sharper pictures than those taken with the motor stroboscope are possible if a xenon stroboscope is used (optional item 134/2). If a school does not own a xenon strobe, it should *not* buy one for photography. It is likely to give uneven, poor illumination.

The procedure is the same as for motor strobe photography except that the illuminating projector and motor strobe are not needed. It is essential to have good blackout and to direct the beam from the xenon stroboscope *along the path of the ball.* It should *not* be used as a general floodlight; this will produce pictures lacking contrast and showing too much background.

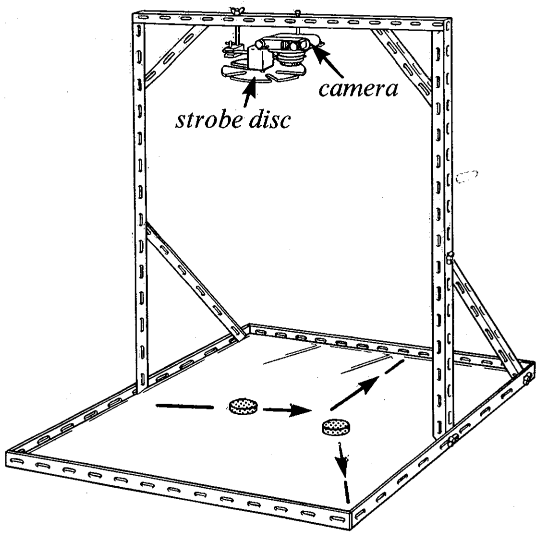
Method 3: Using a Polaroid* camera and a motor stroboscope

A Polaroid camera could be used. For details, consult the company.

* Polaroid cameras (for educational use) can be bought free of import duty, even so, their purchase is hard to justify. Contact Polaroid (U.K.) Ltd., Ashley Road, St. Albans, AL1 5PR.

MOTION ON THE FLOOR (GLASS SHEET)

For collisions in two dimensions, set the camera above the experiment, pointing straight down. The gantry illustrated (item 161) is very useful.



Or a gantry can be improvised from trolley runways, lab stools and tables. Support the runways as a bridge above the glass plate. Stools stood on tables make suitable supports. Support the camera and strobe disc on retort stands clamped to the runways.

Alternatively, the camera may be horizontal, with a small front-surfaced mirror at 45° so that the camera looks down on the moving object.

APPENDIX 2

PROCESSING FILMS IN THE LABORATORY

EQUIPMENT

The items 171 apply to Method A below. The materials are needed for Methods A and B.

The equipment can be obtained as a kit, item 171, or the separate items can be assembled as follows:

3 beakers 50 cm^3, to hold cassette immersed	item 171A
1 twiddle stick (slotted wooden dowel stick, to fit cassette spool; or a piece of PVC tubing)	171B
3 corks (to wedge cassette in beaker)	171E
1 holder for printing paper	171C
2 developing dishes	171D
masking tape	

Materials for taking pictures‡:
Kodak 'Tri-X' or 'Plus-X' film or Ilford HP4 film in 20-exposure cassettes
developer: e.g., 'Suprol' or 'Qualitol' made by May and Baker
acetic acid, 3% solution
fixer, with hardener: e.g., 'Amfix' made by May and Baker

Materials for making prints:
Kodak 'Instafax' offset negative paper, contact speed*
Kodak Universal developer (in 500 cm^3 bottles)
Kodak 'Kodafix' fixer (in 500 cm^3 bottles)
Kodak Ready-mounts 24 mm × 36 mm (latex adhesive), (in boxes of 50)**

METHOD A

This technique is strongly recommended, as the whole process is carried out in front of the class without blackout. The film is developed and fixed by winding and unwinding it inside the cassette which is immersed in liquid. A negative can be developed and projected on a large screen within 10 minutes of making an exposure.

Prints for analysis by pupils can be made quickly on projection paper, so the whole process from taking the original picture to giving each pupil a print can be carried out in one double period in the laboratory.

The description that follows applies to one particular developer used with one particular film. Whichever film or developer is used, *it is essential to follow the maker's instructions.*

The film used must not be longer than a 20-exposure length otherwise the pumping action which takes place in the cassette will be ineffective.

The liquids used may irritate the fingers handling the cassette; so for those with sensitive skins we recommend the use of rubber gloves.

Taking the picture Load the cassette into the camera, as instructed in the camera manual. Make two additional blank exposures at the beginning of the film. Then make 16 (or less) exposures of the experiment. Wind the 20-exposure film back into its cassette, leaving the tongue and 2 cm of full-width film protruding. See sketch *i*.

Cut the tongue off and bend the last 2 cm of film round the cassette, and anchor it with masking tape (NOT Sellotape) as in sketch *i*.

Developing 1. Insert the twiddle stick, making sure that the slot in the end of the stick engages with the drive spigot inside the end of the film spool. (See sketch *ii*).

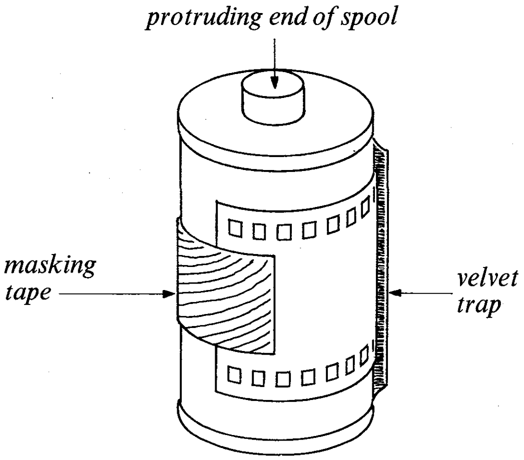
Try winding the film on the spool (anti-clockwise) and then unwinding it until it is against the inside of the cassette. Do not overdo the

‡ Kodak 'Monobath' was suggested in the first edition – it combines developer and fixer in one liquid – but it has been discontinued. If a fresh supply becomes available, the cassette may be processed with it in a single beaker.

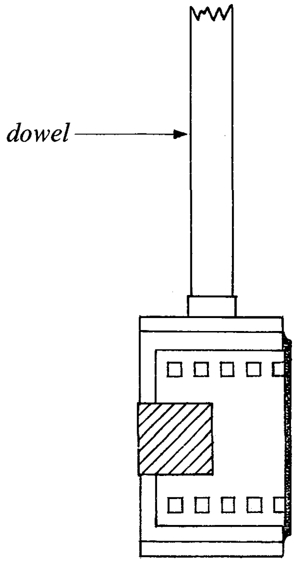
* Order 'Instafax' from London distributors:
Oce-Sky Copy Ltd., 412–420 The Highway
London E.14 (Tel. 01–790–0290)

** Order Ready-mounts from
Crown Manufactory, Chapel Walk,
Masbrough Street, Rotherham, Yorkshire S 60 1EP

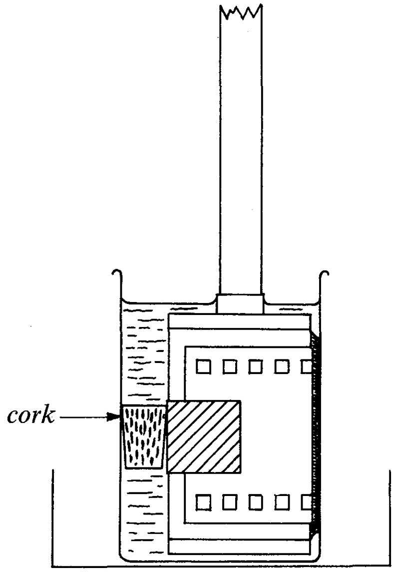
(i)



(ii)



(iii)



unwinding as this may detach the film from the spool.

2. Take three 50 ml beakers and label them A, B and C respectively. Into beaker A pour 40 ml of developer, into beaker B 40 ml of 3% acetic acid and into beaker C 40 ml of fixer. The three beakers are best placed in a large dish because there may be spillage. The solutions should all be at about the same temperature – between 18°C and 25°C.

(Choice of developer and fixer for this kind of work is not critical, although the fixer should be of the rapid fixing variety.)

3. Lower the cassette into beaker A and wedge the small cork between beaker and cassette to prevent the latter turning. (See sketch *iii*).

Now rotate the twiddle stick. As the film is wound and unwound the developer is 'pumped' between the turns of film. Continue for about 2 minutes then remove the cassette from the beaker and transfer it to beaker B, carrying over as little developer as possible. Twiddle in the acetic acid for about 1 minute then transfer the cassette to beaker C.

Twiddle for about 2 minutes then remove the cassette from the fixer, wash it under the tap to remove surplus solution, detach the masking tape, remove the top end of the cassette and take out the film. Rinse the film in a beaker of water or by allowing cold water to run down it from the tap.

4. After removing surplus water from the film by pulling it between the inside edges of two fingers, cut it, mount it in 'Ready mounts' and project it.

5. If an archivally permanent negative is required, re-fix the negative to harden it and wash with three 2-minute rinses each in a fresh supply of water at 18° to 24°C.

Making prints: method 1 The mounted negatives may be used to produce prints within a matter of minutes if 'projection paper' is used. The paper must be such that it will not fog if exposed to normal tungsten room lighting for, say, half a minute.

Use a 500-watt slide projector and a simple printing frame (item 171C—see details below). Printing can be carried out in a room lit with tungsten lighting or subdued daylight (but not fluorescent lighting).

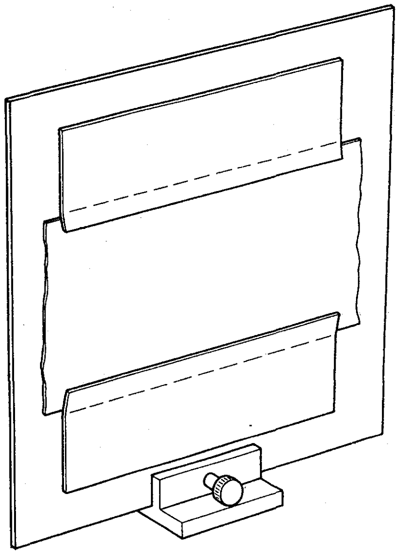
1. Place the projector about 1 metre from the frame. Project an image of the negative chosen on dummy paper in the frame.

2. Switch the projector off and slip a piece of cut paper into the frame. A suitable size is 20 cm × 12 cm. Expose for about 5 seconds to the light from the projector.

Develop the paper immediately, face down, in a dish of developer for half a minute.

Rinse the print briefly in clean tap water, preferably at about 20°C, to remove excess fixing salts.

If the print is to be preserved, wash it more thoroughly for about 20 minutes in running water.

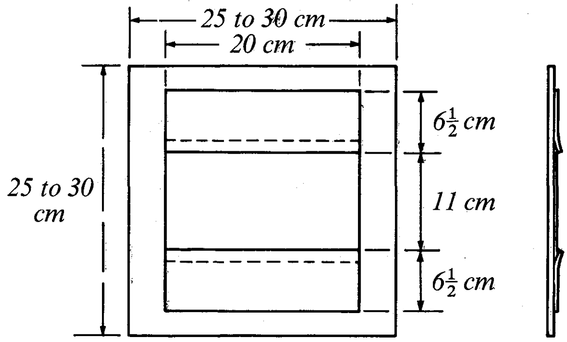


The printing frame This is available in the photographic accessories kit (item 171). Or it can be made as follows:

Stick a piece of thin black card 20 cm by 24 cm on a sheet of hardboard 28 to 30 cm square.

Cut four strips of black card, two 20 cm × $6\frac{1}{2}$ cm, and two 20 cm × 6 cms. Stick them together to make two double-thickness strips with the wider one overlapping the other. Stick the double strips down on the large card so that they form a channel into which a strip of the printing paper, 20 cm by 12 cm, can slide. (Bulldog clips will suffice instead, but the paper will curl.)

The whole frame may be supported vertically in a slotted base (item 30).



METHOD B

In this method 35 mm film is loaded from the camera or from the cassette into a conventional developing tank in a daylight changing bag. Or a daylight loading developing tank may be used. In either case a length of film can be cut from the length originally loaded, leaving the remainder in the camera or the cassette.

Take into the changing bag: (a) the camera, (b) the developing tank and spiral, (c) a pair of scissors (round-nosed to avoid cutting the material of the bag).

Then close the bag and carry out the following operations *in the bag*:

1. Open the camera. Cut the film across the last unexposed negative. Feed the exposed portion of the film into the spiral, *without touching the emulsion*. Close the lid of the developing tank. Then remove the tank from the bag.

You may wish to practise this operation with a dummy film. Once the tank is closed, remove it from the bag and proceed with the developing thus:

2. Add the correct quantity of developer, and agitate the spiral for 10 secs of each minute for the appropriate time.

3. Pour off the developer and replace by the correct volume of 3% acetic acid as a stop bath. After a minute, pour off the stop bath and replace it by the correct volume of fixer. Agitate occasionally for at least 2 minutes (longer if permanent negatives are required).

4. Pour off the fixer (which can be stored for future use) and let water run through the tank for five minutes. If time presses this may be cut to one minute provided that the film is thoroughly washed later.

5. Rinse the film in water to which a few drops of wetting agent have been added.

Remove from the tank and inspect. Select a suitable negative for discussion and cut it from the film with scissors.

6. This negative can be rinsed in methylated spirit and dried over the exhaust from the projector to speed up the process.

7. Sandwich this negative between two 50 mm glass slides or mount in Ready-Mount (latex adhesive) cards, and project on a screen or the blackboard using the slide projector.

8. *For a falling ball* chalk in the positions of the ball and the scale for discussion.

Certain combinations of film and combined developer/fixer appear to produce softening of the gelatin to such an extent that immediate projection is not possible. In any case the negative will still be soft and needs careful handling even when immediate projection appears to be possible.

Making positive prints: method 2 The best method for making positive prints is given in Method A above. An alternative, more traditional, method is given below.

Copies for class use can be made by enlargement through the local chemist, but the cost is high (postcard enlargements are suitable). If the teacher prefers to do the enlarging himself in the dark room, lightweight projection paper is very suitable. This paper is processed in the same way as any other bromide paper, costs roughly half as much and will take pen or pencil readily.

The procedure is:

1. Set up the enlarger to give a magnification of about 10.

2. Expose, after making the usual test strips, on strips of the paper (about 5 cm × 25 cm).

3. Develop for 1 minute.

4. Rinse in a stop bath and fix for 10 minutes.

5. Wash for at least 10 minutes and then dry.

Method 3 Poorer prints can be made using document paper and a 50 mm slide projector.

This avoids the use of a dark room, providing the laboratory can be blacked out to normal standards, because the paper can be handled in subdued tungsten lighting (not fluorescent).

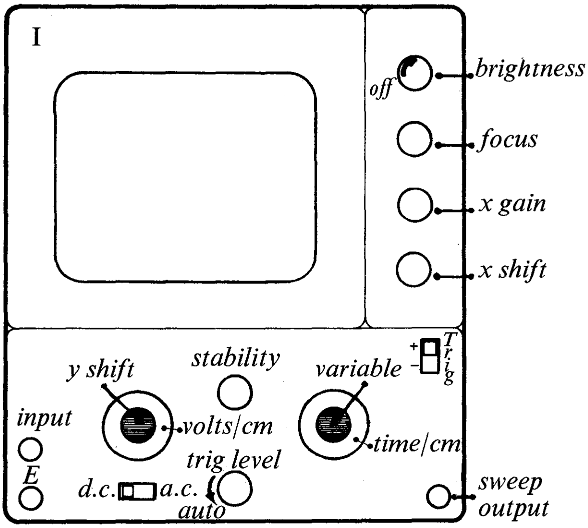
Method A (above) can then be followed.

APPENDIX 3

OPERATING INSTRUCTIONS FOR CATHODE RAY OSCILLOSCOPES

Since the first edition of the Nuffield Guides, several manufacturers have produced oscilloscopes specifically designed for school use, both as demonstration instruments (single beam and double beam) and as instruments for pupils to use.

Inevitably they have features in common; but it is not possible to write detailed instructions which will apply to all varieties. So the following notes only give general advice and guidance, to supplement, but not replace, the instructions given in the manufacturer's handbook.



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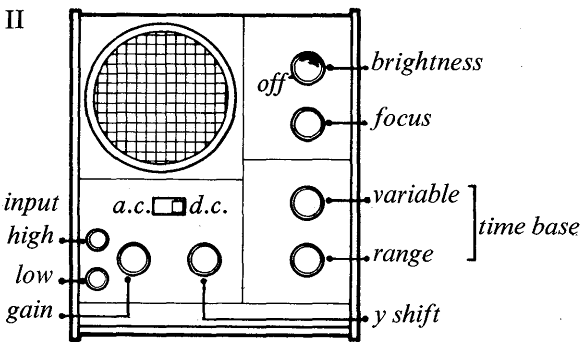


GENERAL NOTES

Controls Sketches I and II show the controls available on two typical CROs. These controls divide into three groups:

A. TUBE CONTROLS: 'Brightness' (or 'Brilliance'), often coupled with the mains ON-OFF switch; and 'Focus'.

B. X-INPUT AND TIME-BASE CONTROLS: 'T.B. Range', 'T.B. Variable', 'X-Shift' and possibly 'Stability' and/or 'Trig Level' controls.

C. Y-INPUT CONTROLS: 'Y-Shift', 'Y-Gain', and an input selector switch. In the case of a double beam oscilloscope, there is a set of these controls for each beam.

Preparation for use To prepare the CRO for use, plug it into the mains supply, switch on and then set the controls as follows:
'Brightness' switched to 'ON' but in minimum position (fully anticlockwise)
'Focus' in the mid-position
'X-Gain' (if provided) at minimum
'X-Shift' (if provided) in the mid-position
Time base controls: use the middle T.B. range with the variable control in the mid-position. Set 'Stability' and/or 'Trig Level' controls as indicated in the manufacturer's handbook.
Y-Input controls: set the Y-Gain at about 1 volt/cm (or mid-position): set the Y-Shift at its mid-position, and the input selector switch to 'D.C.' or 'direct'.

After a warming-up time of about $\frac{1}{2}$ minute, turn the 'Brightness' up until a trace appears and then set that control so that the trace is clearly visible but not excessively bright.

If no trace appears, leave the 'Brightness' in its fully clockwise position and adjust the 'Shift' controls *slowly* until the trace appears. This is best done by rotating 'X-Shift' backwards and forwards whilst *slowly* advancing 'Y-Shift' from the fully anticlockwise position. When the trace is found, at once reduce the 'Brightness' to a convenient level. With those oscilloscopes not fitted with an 'X-Shift', it will only be necessary to adjust the 'Y-Shift'.

If a trace still cannot be found, then it is probably due to a wrong setting of the 'Stability'/ 'Trig Level' controls and their adjustments should be checked with the handbook instructions.

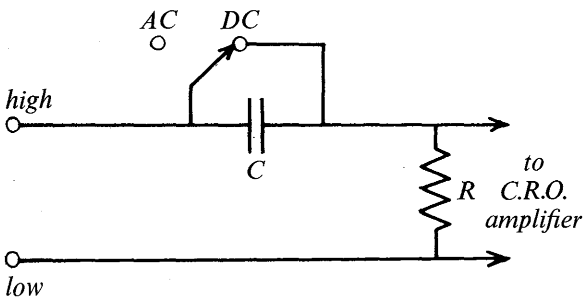
Alternatively, switch the time base off and find the spot by using the 'X-Shift' and 'Y-Shift' controls, as above. With instruments not fitted with an 'X-Shift', the 'T.B. Variable' control may perform this function when the time base is switched to the 'OFF' position.

Now centre the trace with the 'Y-Shift' (and 'X-Shift' if provided) and adjust 'Focus' to give a well-defined trace. With some oscilloscopes, it may be impossible to obtain a sharp focus when 'Brightness' is set near maximum. If so, the brightness should be reduced (turned anticlockwise) until a sharp focus is obtained.

Applying the input The input voltage to be displayed is applied between the Y-input sockets. The socket marked 'earth' (or 'E' or '⏚') or 'low' should be connected to the part of the circuit, if any, at earth potential, the other socket ('high') going to the part not at 'earth' potential. This is particularly important when the oscilloscope is supplied from a source which has one side of its output earthed.

The 'Y-Gain' control will now need adjustment to give a trace of convenient peak-to-peak height.

A.C./D.C. switch The input selector switch should be set to 'D.C.' or 'direct', even when the CRO is used for displaying varying p.d.'s. In the 'A.C.' or 'via C' position, there is a capacitor in series with the input in order to separate the alternating components of the input from any steady voltage also present which might deflect the trace off the screen. When used to display pure alternating voltages, setting the switch to 'A.C.' or 'via C' causes a smaller deflection at very low frequencies and distortion of the waveform if it is not sinusoidal.



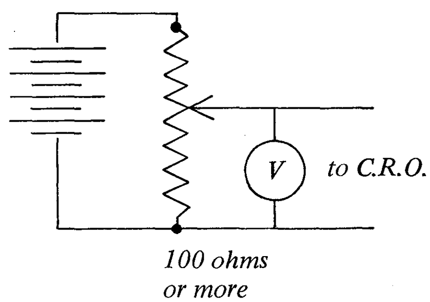
Adjusting the time base controls With simpler class oscilloscopes, time base triggering is automatic when an input signal is present. In other cases, the setting of 'Stability'/'Trig Level' controls should be made in accordance with the manufacturer's instructions.

Normally, the 'Trig Level' should be set to the automatic ('Auto') position, if provided.

When the p.d. to be displayed is applied to the Y-input sockets, it will be necessary to adjust the 'Range' and 'Variable' controls to achieve a suitable trace. These controls change the speed with which the spot moves across the screen; and naturally the settings required will depend on the frequency of the input signal. As a general guide, the 'Range' control should be turned until about 10 cycles can be seen and final adjustments then carried out with the 'Variable' control.

However, if the time base 'Range' is calibrated, it is necessary to set the 'Variable' and 'X-Gain' controls to specified positions in order to obtain the calibrated sweep speeds.

Calibrating the CRO Y-Input A continuously variable 'Y-Gain' control is often only roughly calibrated. To calibrate the Y-input more reliably, the circuit shown may be used. The potentiometer is adjusted so that 5V is applied, and the Y-Gain altered until the spot has been



deflected through 5 graticule divisions from its zero position. One graticule division then corresponds to an input p.d. of 1 volt. When the CRO is used as a d.c. voltmeter it is usually easier to keep the time base switched off.

PRACTICE

Familiarity with the function of the various controls is important. Experience can be gained by using a 50-Hz alternating voltage, (from a low-voltage transformer) as input and exploring the action of the various controls. Oscilloscopes are electrically robust, provided the voltage applied does not exceed the limit stated by the manufacturer—usually about 200V. To avoid screen damage, excessive brightness should be avoided especially if the time base has been switched off.

OTHER FACILITIES

Most CROs allow the *time base* to be switched 'OFF' and an external p.d. to be applied to deflect the spot horizontally (X-input); though with some, the coupling between the input socket and the internal amplifier is via a capacitor so that steady voltages give only a momentary deflection.

A *Z-input* allows the trace brightness to be varied by means of a sinusoidal or square-wave input applied between the 'Z-input' socket and the 'earth' socket. The magnitude of p.d. required to do this will be given in the manufacturer's handbook.

A 'Sweep Output', 'X Out', or 'TB Out' socket provides a voltage, relative to 'earth' which is proportional to the time-base voltage applied to the X-plates. Generally, only small currents can be drawn from this output without distorting the time-base waveform, but this facility may be used to trigger any transient effect repeatedly so that a steady pattern appears on the screen.

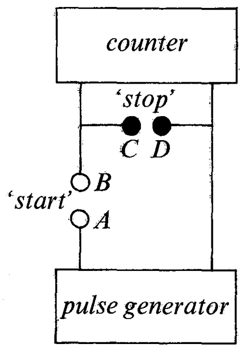
An *'External synchronisation'* ('Ext Synch') socket—which usually serves as 'X-input' when the time base is switched off—allows the sweep to be triggered by an external signal. Details of its use should be found in the manufacturer's handbook.

APPENDIX 4

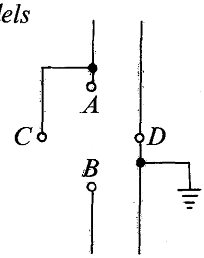
USING THE TIMER-SCALER AS A CLOCK

The Nuffield type of scaler has an internal oscillator which makes sharp pulses at a known frequency. This is usually 1 kHz but in some models, 100 Hz or 50 Hz is provided. When the output of this oscillator is connected to the counter, the counter records at a steady rate and the instrument becomes, in effect, a clock. If the oscillator frequency is 1 kHz, the clock measures time in units of a millisecond.

To time an event, the beginning and end of that event are made to connect and disconnect the oscillator and counter. This is achieved by means of mechanical switches or else phototransistors connected between sockets on the front panel of the scaler. In essence, the timing sockets are connected as in the sketch.



arrangement of sockets on some models



To time an event using switches which are *closed* by the beginning and end of the event, the first switch is connected between the START sockets, and the second between the STOP sockets. The START switch, which is operated first, must remain closed at least until the STOP switch is closed.

To time an event using switches which are *opened* at the beginning and end of the event, the switches are again connected to the START and STOP sockets, but the switch which starts the clock is the one connected to the STOP sockets. The second switch is connected to the START sockets; and it disconnects the oscillator when opened and thus stops the clock.

Events can also be timed using a single switch. If the switch is *closed* by the beginning of the event and opened at the end, then it should be connected between the START sockets, the STOP sockets being left without any connection. If, on the other hand, the switch is *opened* by the beginning of the event, etc., then it should be connected to the STOP sockets with the START sockets linked.

Photodiodes or photo-transistors may also be used as switches. When the photo-sensitive device is strongly illuminated, it conducts a relatively large current and if connected between a pair of sockets, it behaves like a closed switch. In the dark, the conduction current is much smaller and the device is equivalent to an open switch.

When using such photo-sensitive devices, correct operation will only be achieved if they are connected to the sockets the 'right' way round. The 'right' way may be found by trial and error or by consulting the manufacturer's instructions.

If two photo-transistors are used to measure the velocity of a trolley at two stations—so that the trolley's acceleration can be estimated—the two can be connected in series, both illuminated, and the combination connected to the STOP sockets, (with the START sockets joined together). Then if either of the photo-transistors is shaded from light, the counter will show the time of that shading.

In some instruments, triggered or gated switching is available in place of, or in addition to, the simpler system described above. The detail of using the scaler-timer with that facility must be learnt from the manufacturer's handbook. In general terms, a *momentary* connection between the START terminals will cause the timing to start; and thereafter timing continues no matter what happens to that connection. Timing only stops when the STOP terminals are *momentarily* connected together. Some instruments are constructed so that operation on a *momentary break* may be selected, rather than on a *momentary make.*

APPENDIX 5

Suppliers of Solid Carbon Dioxide

IMPERIAL CHEMICAL INDUSTRIES LTD supply rectangular blocks of dry ice through their 'Merchants'. A block may be collected from a Merchant's Depot or in most cases the Merchant can arrange for delivery by road transport or rail. To find the address of the nearest Merchant, consult any of the following ICI Sales Offices:

(Main Office and North Eastern Sales Office)
ICI, Industrial Products Department, Agricultural Division, PO Box 1, Billingham, Teesside, TS23 1LB
Telephone: 0642 553601

ICI, Imperial House, Donegall Square East, Belfast, BT1 5HQ
Telephone: 0232 27741

ICI, Britannia House, 50 Great Charles Street, Queensway, Birmingham, B3 2LU
Telephone: 021 236 7070

ICI, PO Box 100, Thornton House, Bridge Street, Bradford, BD1 1HP.
Telephone: 0274 29530

ICI Severnside, Hallen, Avonmouth, Bristol, BS10 7SJ
Telephone: 02752 3601

ICI, 15 Park Place, Cardiff, CF1 3TR
Telephone: 0222 22731

ICI, 4 Blythswood Square, Glasgow, G2 4AB
Telephone: 041 248 5020

ICI, Cunard Building, Liverpool, L3 1EQ
Telephone: 051 236 8000

ICI, PO Box 19, Templar House, 81–87 High Holborn, London, WC1V 6NP
Telephone: 01 242 9711

ICI, Sunley Building, Piccadilly Plaza, Manchester, M60 7JT
Telephone: 061 236 8555

There are Depots in Aberdeen, Belfast, Birmingham, Bradford, Edinburgh, Glasgow, Great Yarmouth, Grimsby, Guernsey, Hull, Leicester, Liverpool, London, Londonderry, Manchester, Nottingham, Shepton Mallet, Southampton, Tyneside, Wellingborough.

THE DISTILLERS COMPANY supply cylindrical blocks ($11\frac{1}{2}$ kg).

The following Sales Offices will give the address of the nearest supplier:

(Main Office)
The Distillers Company (Carbon Dioxide) Ltd, Cedar House, London Road, Reigate, RH2 9QE
Telephone: 74 47611

(Northern region)
Cheshire House, Booth Street, Manchester, M2 4AH
Telephone: 061 236 5151

(Southern region)
Broadway House, The Broadway, Wimbledon, SW19 1RN
Telephone: 01 542 4661

(Midland region)
Station Road, Coleshill, Birmingham, B46 1JY
Telephone: 0675 62695

(Scottish region)
14 Manor Place, Edinburgh, EH3 7DD
Telephone: 031 226 7134

There are Factories, Depots and Agencies in: Alloa, Aberdeen, Bath, Birmingham, Birtley, Bootle, Dagenham, Edinburgh, Glasgow, Grimsby, Hammersmith, Hull, Liverpool, London Docks, Manchester, Pontypridd.

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General Editors
Eric M. Rogers
E. J. Wenham

Contributors
G. E. Foxcroft
D. W. Harding
J. L. Lewis
A. W. Trotter

This volume contains the material for the fourth year of Revised Nuffield Physics. The main topics are: Mechanics continued: Newton's Laws, momentum and momentum conservation, kinetic energy; Gases; Kinetic theory and predictions; Conservation of energy; Human energy and power; Electricity continued: voltage, Ohm's law and others, power in electric circuits; electrons.

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